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REPORT 26-02-R-004

DEVELOPMENT OF A WES CENTRIFUGE

FINAL TECHNICAL REPORT

by

A N Schofield and R S Steedman

1 September 1992

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London England

CONTRACT NUMBER DAJA45-91-C-0012

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1 September 1992

SUMMARY

ANS&A has commenced its review of the requirements for items of centrifuge instrumentation and equipment which will meet the initial needs of each of the different Laboratories participating in the development of the Army Centrifuge Center at WES. Interaction with the Laboratories has taken place through the Centrifuge Coordinating Committee, which was established in January 1992 to review the needs of the Laboratories for test instrumentation, equipment and training.

This has led to a great expansion of the range of capabilities now expected from the centrifuge center, a significant development from the more geotechnically focussed activities of a WES Centrifuge Center put forward in ANS&A's original response to the WES Broad Agency Announcement of December 1988.

A second important new development has been in the area of training, which is now envisaged as taking place entirely on the Station under the direction of an ANS&A Associate, resident in Vicksburg for a period of at least two years.

ANS&A recommends that orders be placed for initial centrifuge appurtenances, compatible with the Acutronic 684-1 presently on order for WES, from the list of instrumentation and equipment kits presented in this report. These kits have been prepared on the basis of an evolving range of capabilities, starting with basic materials handling using existing centrifuge technology, and progressing into fields which will represent new and challenging areas of equipment development.

LIST OF KEYWORDS

centrifuge
test
model
capabilities
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assurance
containment
buildings
equipment
instrumentation
safety

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LIST OF APPENDICES

1.0 DEVELOPMENT OF A WES CENTRIFUGE

1.1 BACKGROUND

This report is one of a series of reports prepared by Andrew N Schofield & Associates Ltd (ANS&A) addressing the development and commissioning of new capabilities for physical modeling research at the Waterways Experiment Station (WES), through the acquisition of a powerful centrifuge facility. The research described herein forms Phase 2a and 2b of the programme of work first proposed under ANS&A's response (of 17 April 1989) to the WES Broad Agency Announcement (BAA) of December 1988. A number of ANS&A Associates have contributed to the preparation of this report by the Principal Investigators, including Drs R Phillips, C Savvidou, X Zeng and C Smith. Their assistance is acknowledged. Phase 1 of this project, entitled "Safety Factor Analysis for Centrifuge Systems", addressed the specification, Quality Assurance (QA) procedures and safety of operations that would be required to successfully commission a new centrifuge center at WES. In the Final Technical Report under Phase 1 (Contract No. DAJA45-90-C-018) it was recommended that WES should buy the Acutronic 684-1 centrifuge subject to the implementation of QA procedures designed to ensure the swift integration of the new facility into the research activities of WES.

In January 1992 WES contracted with Acutronic USA to supply and install a powerful centrifuge capable of providing novel capabilities in research for all of the Corps Laboratories. This wide range of capabilities sought by the Corps of Engineers for their new centrifuge is made clear in the WES Miscellaneous Paper GL-91-12 "Large Centrifuge: a critical Army capability for the future" dated May 1991 and published in January 1992.

1.2 REVIEW OF ANS&A'S RESPONSE TO THE BAA

The WES Miscellaneous Paper GL-91-12 represents an important expansion of the requirements for application of centrifuge modeling outside the fields in which ANS&A's March 1989 response largely concentrated (the geotechnical and earth sciences area). Considering the WES centrifuge center to be a facility providing experimental data across the field of civil engineering provides an exciting opportunity for novel experiments in many diverse fields. However this represents a significant increase of the scope of work beyond that which was envisaged in the initial tasks of ANS&A's March 1989 response to the BAA.

In considering the equipment needs to service such a wide range of potential users and their experiments ANS&A requested to meet with the authors of Paper GL-91-12 to discuss how each Laboratory envisaged its use of the new facilities. (This group was formally convened in early 1992 as the Coordinating Committee.) Clearly in some areas established technology in equipment and instrumentation will be quite readily transferred to the WES center. However in other fields, for example hydraulics, the new opportunities provided by the centrifuge will inevitably take longer to be fully exploited. At this early stage, therefore, the priority has been placed on demonstrating capabilities rather than on actual experiment. In some of these fields ANS&A Associates are already active in centrifuge model tests but in all cases the definition of experiments requires an increase in the time needed for interaction between ANS&A and staff in the wide range of USAE Laboratories beyond that envisaged in ANS&A's reponse to the BAA.

ANS&A's response envisaged the possibility of a group of USAE staff visiting Cambridge, England, to be trained in techniques already well established there. However the opportunities for travel are now less than was anticipated and ANS&A needs to interact with a wider range of people than was envisaged. There is clearly a need for review of the implications of these developments on ANS&A's March 1989 response to the BAA.

ANS&A submitted its response to the BAA of December 1988 in March 1989. That response described how, by achieving a set of initial research tasks, new capabilities in the field of physical modelling could be achieved with a novel centrifuge facility at WES. Since that time there has been a substantial change in emphasis both in the range of models that are to be undertaken and in the specification of the centrifuge itself. For example, for testing at above 200g it was proposed that the standard swing would need to be removed and replaced with a special aerodynamic cylindrical container with a hemispherical base. As the specification of the centrifuge was developed ANS&A recommended that this concept be changed in favour of a standard square platform capable of carrying packages throughout the range of operations to a maximum level of 350g.

This development then permitted an important increase in opportunity for widening the range at which many other model tests could be undertaken. A normal operating g level of 280g was then defined, opening the door to the use of more complex actuators and probes (which would have been difficult to deploy on the original high g container) at g levels considerably in excess of the original 200g limit initially set for a flat platform.

In fields such as earthquake engineering, it was envisaged that dynamic excitation should be sought for models of upto 500 kg at this limit of 200g. In the initial research this target seemed unattainable but a spring actuator system now under development at Cambridge shows promise of working at upto 280g on a mass of around 200 kg. This level of performance, shaking a prototype mass of 280 x 280 x 280 x 200 = 4.4 million tonnes, would exceed that suggested in the BAA response (200 x 200 x 200 x 500 = 4 million tonnes).

Similarly, in the field of environmental studies, the increase in the available working g level on a flat platform provides enhanced opportunities for research in standard tubs which are more readily transportable and which can made environmentally secure. Current research in this field is addressing the use of model contaminants which will provide the capability to study problems involving both adsorption and diffusion.

The change in emphasis in the centrifuge since ANS&A's response to the BAA has been to facilitate routine operations at higher g's. A new list of demonstration experiments has evolved from the concept of initial research tasks. These demonstrations of new capabilities will require carefully planned interaction with other Laboratories, training programmes and 1g experiments during the period leading upto the commissioning of the centrifuge itself. To oversee the commissioning of capabilities, including acceptance of equipment and training of engineers and technician staff, ANS&A will second an Associate to WES for a period of around two years.

1.3 COORDINATING COMMITTEE

Following the placing of the contract for the centrifuge with Acutronic USA in January 1992 a Coordinating Committee with representatives from each Laboratory was formed to review the needs of the individual research groups for test instrumentation, equipment and training.

The instrumentation and equipment lists, which are described in following sections of this report, have been developed by ANS&A following detailed discussions with members of the Coordinating Committee and with careful consideration of the achievement of a maximum range of new capabilities at a minimum expenditure.

The tasks and capabilities that will result from the performance of these items of equipment and instrumentation will need to be reviewed and revised by individual members of the Coordinating Committee. A plan, programme and budget for the training of staff in the use of the centrifuge and the performance of their initial experiments will need to be set and coordinated within an overall plan for the commissioning of the centrifuge facility.

Each Laboratory plan will have instrumentation and equipment procurement requirements which will need to be reviewed by ANS&A. Where items involve the safety of the Acutronic centrifuge (for example the platform stresses induced by a stiff rectangular strongbox and the safety of the box itself) decisions will need to be taken by ANS&A, acting on behalf of WES in the first instance, concerning design procedures.

In process of considering the increased scope of work with the Coordinating Committee two questions arose which have had a direct consequence for the containment structures. The first of these concerns the Hydraulics Laboratory need for high water flow rates through a model. ANS&A envisages an item that can be attached to the existing centrifuge; however the water supply and the discharge against the wall of the chamber will require to be given special consideration by the building designer.

Secondly the question arose of controlling temperatures in models with greater accuracy than was anticipated in the Acutronic centrifuge chamber design. Rather than attempting to achieve full air conditioning in the centrifuge chamber during a long centrifuge flight ANS&A have suggested that a more practical and economical alternative would be to provide thermal barriers around or within the model container itself. Temperature control within the model test equipment therefore becomes a basic need and is not associated simply with the needs of the Cold Regions Research Laboratory.

2.0 WES EQUIPMENT NEEDS AND INITIAL TASKS PRIORITISED

2.1 EQUIPMENT NEEDS

In ANS&A's 'March 1989' response to the BAA a list of instrumentation and equipment items was proposed by which a set of tasks could be accomplished. These 'March 1989' instrumentation and equipment items for the WES centrifuge centre were reviewed in the light of the WES Miscellaneous Paper GL-91-12 "Large Centrifuge: a critical Army capability for the future" dated May 1991 and published in January 1992 and of research work undertaken in Phase 2 and reported in Appendices to this 1992 report. The review led to significant revisions. The decision that the centrifuge should fly a 1.3 m x 1.3 m swinging platform at 350 g affects some items and not others.

Equipment for centrifuge use has been grouped into 'kits', classified as either 'basic items', which would be typically for early use both off and on the centrifuge for short duration tests without temperature variation and 'design and development items' which by their nature will require careful consideration before being specified in detail. There are twelve items in total. An initial 'basic' test control and data aquisition system is proposed but further enhancements of this system will be required as the centrifuge capabilities are developed. A conceptual upgraded system is discussed in Section 3.9; a detailed specification of necessary further test control and data aquisition systems will be prepared as a deliverable with the initial 'basic' system.

BASIC ITEMS

(1) A cylindrical tub of 1.2m diameter, to contain soil at 350g, tub extension piece, with a single-point sand-pouring hopper for dry placement of sand, and a vacuum seal for saturating sand with deaired water after placement with provision for air pressure and vacuum control;

(2) Pore pressure and displacement transducer system, with basic trolley mounted test control and data aquisition system, suitable for limited dynamic application to earthquake and blast model test data, with specification of enhanced test control and data aquisition system;

(3) In-flight soil testing cone penetrometer, including drive system and instrumented probe with piezotip;

(4) Basic loading systems for circular plate bearing tests, with appropriate load cells;

(5) Weapons effects blasting liner for use in the 1.2m diameter tub with pressure blow off plate and with torospherical ends (for use at 1g) and a flat base plate for use in a 1.2 m tub both in-flight and at 1g to define blast test safety requirements, and blast test data capture and processing requirements, in early tests prior to centrifuge delivery;

(6) Earthquake box, including actuator, suspension system, equivalent shear beam soil container, and appropriate transducers and signal conditioning interface box. The current design of the Cambridge 1992 spring actuated model

earthquake system envisages an equivalent shear beam soil container on a shaking platform with an actuating spring and mass, and a spring release mechanism and a brake which are integrated in a unit that is mounted on the Cambridge 10 m centrifuge platform. Four columns with flexible straps support the shaking platform and allow lateral movement. A review and redesign of this system to take advantage of 280 g normal operations on the WES platform and of the WES platform length and reaction mass, will define the performance that may be achieved at WES for cost comparable to Cambridge cost.;

(7) Downward hydraulic gradient consolidometer for tub, tub extension and system for extraction of a clay specimen from a tub;

(8) Plane strain box, without windows, with seal for vacuum saturation of a sand specimen, adaptors for use with the downward hydraulic consolidometer;

(9) Hydraulic and pneumatic systems to model excavation and surcharge, in-flight sand hopper for stage construction using sand fill for use with the plane strain box.

DEVELOPMENT ITEMS REQUIRING DESIGN STUDIES

All items of equipment will require design and development. However certain items of equipment have been identified as requiring further design studies during the coming year to establish their feasibility for operations on the WES centrifuge, and from which detailed specifications and costs can be prepared, as follows;

(10) Constant temperature and temperature gradient control system based on thermal barriers both external to and within model containers, with a range of sources of heating and refrigeration and a system of temperature sensors and a variable temperature control system, for use both to maintain constant temperature in long duration tests, and in cold regions studies;

(11) Electrically and chemically inert liners within a circular tub, and electrical and chemical probes;

(12) High capacity under-slung water-flow system to platform, stilling tank and flume on platform, with water level and local flow measurement, and stored angular momentum wave generator for flume; prototype system could be proved in Cambridge prior to construction of the full size apparatus.

Each of these items could be developed under a contract between Ciel and WES. Items 1 to 9 are sufficiently well defined for Ciel to be able define a target cost and prepare a quotation. This is possible where the item is quite like an item that is familiar, although it will only have been used on a smaller centrifuge and at lower acceleration. This is not the case with items 10 to 12. Detailed Ciel designs prepared with ANS&A oversight, rather in the manner that Acutronic France's design of the novel WES centrifuge has been augmented by ANS&A acting in a technical quality assurance role, will give WES a good basis for technical and financial control of further equipment developments in these areas. Design studies, undertaken during the coming year, could provide detailed

these areas. Design studies, undertaken during the coming year, could provide detailed cost estimates and specifications for subsequent quotations.

2.2 DEVELOPMENT OF CAPABILITIES

Equipment items would be bought over a period of two years and used to develop new capabilities for each separate WES laboratory. To achieve this given WES's current time and budget constraints there must be changes from the "March 1989" initial tasks. There must not be a long delay before WES personnel in all Laboratories are able to perform model tests and to win contracts for themselves in their fields. Where the March 1989 response proposed initial tasks each beginning in Cambridge under the direction of an ANS&A Associate, it now is proposed that WES staff should take their first steps in centrifuge model testing in Vicksburg. Each Laboratory is represented on the Coordinating Committee and a demonstration of capabilities is envisaged in every field. This has required ANS&A to discuss in detail with the different Laboratories a test within their own area of expertise (although sometimes outside the area of expertise of the Investigators) which will meet their initial needs for experimental data at minimum cost.

The Investigators recognise a risk that WES staff who lack centrifuge experience, and ANS&A staff who are not expert in every field of WES activity, may between them specify detailed designs of items which will not have long term value. Also a disappointment or a failure in any field early in the programme of development of capabilities may be unduly discouraging to WES staff if the experiment in question is conducted on the large and rather demanding new Acutronic centrifuge. Therefore ANS&A plans to bring a small teaching centrifuge to WES and to work with the Coordinating Committee on some aspects of model tests where changes in details of instrumentation and equipment may be made before the centrifuge is delivered or fully commissioned.

The series of tasks now envisaged is considerably larger than in March 1989 and is as follows (item numbers in parenthesis indicate commissioning of a further new item of equipment or instrumentation):

(a) Basic Geotechnical Laboratory capabilities in sand

Sand in tub at various densities and with different water levels tested by cone penetrometer (items 1,2,3); modelling of models tests of bearing capacity of circular loading plates (item 4).

(b) Structures Laboratory capabilities

Blasts in sand layer with various water tables (item 5).

(c) Additional Geotechnical Laboratory capabilities: earthquakes

Earthquake test of liquefaction in confined zones (as in the Lower San Fernando Dam or in the Bolivar Coast Dykes) (item 6).

(d) Additional Geotechnical Laboratory capabilities: clay soil

Basic clay consolidation and modelling of models of plate bearing on clay, leading to a "leaning tower of Pisa" model (item 7); uplift caused by falling water in lock (item 8).

(e) Information Laboratory capabilities

Excavation in front of a wall and surcharge loading behind it; also sand embankment placed on a reinforced layer on a clay foundation (item 9).

(f) Cold Regions Laboratory capabilities;

Thaw-induced settlement and frost heave of pipelines (item 10).

(g) Environmental Laboratory capabilities;

Capped contaminated dredge disposal on freshwater lake bed with detection of pollutant transport (pollutants may be sodium chloride, cadmium chloride, or technisium) from the consolidating contaminated layer into the layers of sediment below and the cap layer above, with diffusion, dispersion, and sorption in adjacent layers depending on the pollutant used (item 11).

(h) Coastal Laboratory capabilities

Wave loading on a coastal dyke using wave tank; also packing changes and stress increase in dolos in a breakwater under storm wave loading (item 12).

(i) Hydraulic Laboratory capabilities

Head loss through rock dyke in high flow capacity flume; experimental development work will be required in Cambridge in collaboration with WES to explore the stilling of high flow rates on a beam centrifuge and the potential for the use of a drum centrifuge as a long flume before high capacity water flow system and stilling tank arc made (also item 12).

To train Geotechnical Laboratory centrifuge technicians and research staff will require a plan, a programme, and a budget within that Laboratory. If Geotechnical Laboratory technicians, under the direction of one ANS&A Associate, were to conduct the whole sequence of test series listed above alone, the programme would be likely to take 4 to 5 years, and there would be a long delay before the other laboratories began to understand tests in their fields, to train their own research workers, and to plan and specify such tests, and to report them. A critical activity for the ANS&A Associate based at WES prior to commissioning of the centrifuge will therefore be to enact a programme of in-house training for appropriate WES personnel from each Laboratory. This will be achieved by utilising a small ANS&A centrifuge which ANS&A will bring in specifically for training purposes and equipment and instrumentation commissioning. The success of the commissioning of a new capability will depend on an early commitment by the different Laboratories to training and collaborative experimental work. This will require a plan and programme for each Laboratory which will be

developed through the Coordinating Committee in discussion with ANS&A.

2.3 DESIGN AND MANUFACTURE OF EQUIPMENT

The items described above are specified in Appendix A to this Report in sufficient detail for WES to request a quotation from Ciel for their supply. ANS&A would seek to provide Quality Assurance for all items that are required in the commissioning of capabilities.

ANS&A and the researchers from the specific Laboratories who will use the items will cooperate with Ciel in reviewing the detailed design of these items. In some cases items may be manufactured in the WES workshops of the Laboratory concerned but in such cases a detailed design will be prepared by Ciel to meet the specification agreed with ANS&A and the researcher. The commissioning and calibration of each item will require close cooperation between ANS&A and the researcher involved.

3.0 LABORATORY NEEDS

3.1 BACKGROUND

A particular feature of the WES centrifuge will be its wide application to areas of engineering far removed from the geotechnical field from which the new centrifuge technology has evolved. This is a most welcome development and will provide many new opportunities for novel research application. However to attract sponsors who will fund WES activities in these new areas will require an early demonstration of capabilities on the new facility.

The interest shown by the different Laboratories to the principle of a WES centrifuge is expounded in the Miscellaneous Paper GL-12-91 already referred to in Section 1.1 above. With the centrifuge now a real prospect considerable effort has been expended in meeting with these Laboratories through the Coordinating Committee to discuss their evolving experimental interests, training and equipment needs. This section of the Report addresses each Laboratory in turn and reviews their differing initial requirements from the centrifuge center.

3.2 GEOTECHNICAL LABORATORY

The needs of the Geotechnical Laboratory in acquiring the technology of centrifuge modelling can be classified under several headings. In practice these broad areas, which help to categorise the necessary set of equipment, are the same across all fields, but the wide range of applications which are well established in the geotechnical field and the important role that the Geotechnical Laboratory are taking in the development of the centrifuge center means that the general requirements are best explained by illustration in this field.

First is the requirement for technology transfer in the preparation of soil specimens for centrifuge testing, using clay and sand soils. The initial capability to be commissioned will be in the use of sands, pouring and saturating under vacuum in a circular centrifuge tub and subsequently transporting the model onto the swing for testing. In clay soils the development of a downward hydraulic gradient consolidometer for use in either a circular tub or a rectangular (plane strain) box is envisaged for the preparation of clay specimens, together with the necessary extension units for the model chambers and extraction systems to remove the sample from the tub or box after testing. It is recommended that the capability to prepare models in a circular tub should be acquired before moving on the preparation of models in rectangular boxes. This will clearly have implications for the sequence of tests during the commissioning of capabilities.

The second requirement is to demonstrate a capability of measuring initial conditions inflight through the use of in-situ site investigation (using a cone penetrometer) and by the measurement of pore pressures and displacements of the specimen. These transducers form the 'front end' of the data capture system the requirements for which are described below separately as these apply across all model testing activities.

The third area is the capability of creating a perturbation on the model, which may be as simple as changing a water level or as complex as inducing dynamic actuation at high gravities. The development of actuators may be closely linked to experimental requirements; clearly an earthquake shaker, for example, will be needed to provide a capability in the field of earthquake engineering. But there are other more general purpose items, such as a hydraulic loading system, which are key components within the general set of equipment. These items can be commissioned by application to standard problems, such as the bearing capacity of soil, and are then available for wider use.

The field of earthquake excitation on centrifuges has seen considerable investment over recent years and many successful shakers have been developed for use. Appendix B discusses the issues behind the problem of providing dynamic actuation on a soil specimen under high gravities. Broadly this can be reduced to two separate issues: the nature of the soil containment and the system for dynamic actuation. Although many systems have been developed which have operated successfully at low gravities, to fully exploit the potential of the WES centrifuge it will be necessary for an actuator to operate at g levels around three times higher than any shaker has operated at to date. Developments at Cambridge University using a spring type actuator are expected to provide data in 1992 - 1993; this system may prove mechanically robust enough to operate at the high gravities possible on the WES centrifuge.

3.3 STRUCTURES LABORATORY

A wide range of problems for which the centrifuge can make a valuable contribution have been identified in the area of structures research. However equipment needs are hard to define as the timing of many of the structures projects is short and equipment developed at an early stage which was too specialised would be likely to quickly become redundant.

Current areas of research which would have centrifuge application include (a) the study of damage to tunnels in jointed rock from aerial bombardment, (b) penetration studies using bullets or other projectiles, (c) the placement and stacking of concrete dolos, (d) pavement cratering and (e) shallow buried munitions in rock. Typical soils requirements for models would be tamped damp sand or a clay soil but clearly an important area of future model research will be to develop substitutes for jointed rock.

Equipment ordered at this stage must have wide application and hence should be simple in its design. The key additional requirement for the Structures Laboratory is to provide a blasting capability for weapons effects model testing. This will be best achieved by the early development of a blast liner which can sit inside a standard circular tub (which provides containment in the event of rupture of the inner chamber) and which is isolated from the flat platform by the use of rubber mats and a crushable layer. Such a chamber can be proof tested at 1g with a sequence of charges prior to its use on the Acutronic centrifuge.

3.4 COLD REGIONS

The requirement for capabilities in the field of cold regions research stems both from research in the broadly geotechnical area (frost penetration, permafrost) and from research in the area of ice mechanics (behaviour of sea and river ice, for example). The prime concern for equipment development for cold regions research is to achieve the correct boundary conditions on the model. These include control of heat transfer laterally through the use of insulators on the side walls and control of temperature, and particularly heat flux, on the upper and lower surfaces of the model. Appendix C describes in detail the issues surrounding the modelling of problems requiring cold temperature control.

The development of equipment for thermal control of models would have benefit in the control of temperature cycling during long duration model tests in addition to the capability of studying the transient condition caused by blowing cold or hot winds over the surface of model in flight.

It is envisaged that research and development work in this field will be needed over the coming year to achieve the demonstration of capabilities in the Cold Regions area. Collaboration between the Cold Regions Laboratory and ANS&A Associates in the UK can provide the basis for future equipment specification.

3.5 ENVIRONMENTAL LABORATORY

At present there is little experimental work at WES in the environmental field, except in the area of leaching. The opportunities presented by the new centrifuge will not require a major change in that approach because the volumes of material being handled will remain modest. Environmental liners, which are secured within standard circular tubs for example, may contain only around 0.5 m^3 of soil with a small volume of contaminant. Instead of the contaminant being investigated in a column or beaker the opportunity will exist to explore three dimensional effects with variation of boundary conditions.

Research areas have been identified in (a) subaqueous capping of dredged materials, (b) creation and maintenance of wetlands, (c) performance of hydraulic barriers in landfill sites and (d) validation of groundwater codes for contaminant transport. Of these the performance of capped dredged disposal, investigating leachate production and contaminant concentration as a function of time, will form the demonstration experiment.

In the capped-layer test a depression on the bed of a fresh water lake is filled with contaminated compressible dredgings which are then covered with a cap-layer of soil. Consolidation of the dredgings causes discharge of a finite volume of polluted pore water; some is discharged down into the pores of the soil in the lake bed and some is discharged up into the cap-layer. The transient flow in the cap layer will be governed by diffusion, dispersiory and sorption processes and by any advection due to possible piping, boiling or cracking of the layer material. The design of a cap-layer in a practical problem will involve choice of the material, and of the layer thickness that minimises the risk of there being a

pollutant discharge into the lake water. The Environmental Laboratory task that is envisaged is to perform a model test that gives data capable of being compared with an analysis of the cap-layer problem.

The initial pollutant will be sodium chloride, which can be readily detected with specially designed miniature resistivity probes. For studies involving sorption on soil, cadmium chloride can be used, but it is less safe and less practical to detect. The short lived radio isotope technetium m99 has been used at Cambridge where it was detected using Geiger-Muller tubes and this could also be used for the WES centrifuge tests.

The development work that will be required in the environmental area could be initiated in Cambridge under the supervision of an Associate, Dr C Savvidou, over the coming year and would culminate in the development of a new 850 mm diameter tub capable conducting the proposed experiments on the WES centrifuge (having already explored the problem at low g on the Cambridge centrifuge). There could be cost sharing of such research and development between WES and Cambridge University. The work would be initiated by studies using the new ANS&A small centrifuge which would later be transported to WES for training and equipment development. The research would continue in a specially fabricated high g 850 mm tub for use at WES.

New analytical solutions analysing consolidation and pollutant transport under one dimensional small strain conditions will be developed alongside the model tests, and two dimensional finite strain formulations will be investigated. These can all be incorporated into the WES publications presenting the Environmental Laboratory's capabilities in centrifuge model testing.

3.6 HYDRAULICS LABORATORY

A centrifuge model provides an opportunity to study problems of turbulent flow which are not easily modelled at 1g. Several experiments suitable for modelling on a centrifuge have been identified in discussions with the Hydraulics staff, including, for example, the measurement of forces on gates. However, the experiment which has been selected for the demonstration of capabilities in this field is the nature of head loss through a rock dyke under a high flow rate. In this experiment the same linear scale model is subjected to high rates of flow at a range of different g levels.

There are several obstacles to overcome in the development of equipment to achieve a hydraulics capability. High rates of water flow can be passed onto a centrifuge in flight independently of the standard hydraulic slip rings (which have too little capacity for the flow rates under consideration) but the high flow rates and mechanisms (scoops or troughs) by which this can be achieved inevitably entrap air and make the achievement of a steady and uniform upstream flow condition extremely difficult. As the water flows from the low g environment near the central axis to the high g environment at the swinging platform air will be introduced as the water accelerates towards the outlet into the stilling tank.

Water flow rates of upto 2 cubic feet per second have been stated as a

requirement and this will have implications for the design of the centrifuge containment structure. Water can either flow from above the centrifuge through a pipe or series of pipes near the central axis into a central on-axis tank and thence down the arm to a stilling tank on the platform or be pumped from below the chamber into an underslung doughnut shaped tank which hangs beneath the booms. However the complexities of protecting sensitive and valuable electronic data aquisition systems which will also be mounted on-axis above the centrifuge booms lead to the conclusion that the preferred option is to mount any such system underneath and to keep the electrical and water systems as separate as possible.

The second area of difficulty is to design a stilling tank which can be mounted on the swing (and which will also probably need to support the flume) which can still the water flowing out from the central axis. A long flume, of the order of 2.5 - 3 m is considered to be the minimum necessary for experiments of this type.

This area clearly poses considerable challenge and will require careful collaboration between the research staff of the Hydraulics Laboratory and ANS&A in considering the feasibility and design of a flume with high flow capacity. For this reason it is recommended that a design study be undertaken by ANS&A over the next year to further clarify the requirements and possible design of such equipment. In particular it is proposed that a prototype system could be tested in Cambridge before a full scale facility was ordered for WES.

3.7 COASTAL LABORATORY

The use of the centrifuge for studies relating to the coastal environment is increasing. Experience at Cambridge, where continuing collaboration between Professor Sekiguchi of the Disaster Prevention Research Institute at Kyoto and Dr Phillips has led to the development of wave generators and absorbers, and wave height measuring devices for use in the centrifuge has enabled coastal problems of wave attack to be addressed directly.

In discussion with the Coastal Engineering Laboratory it was agreed that a experiment investigating wave attack on a coastal dyke would be a clear demonstration of capability. This would require a wave generator and long flume to allow for run up against the dyke.

3.8 INFORMATION LABORATORY

The requirements for the Information Laboratory closely follow those for Geotechnical; many of the experiments envisaged are developments of geotechnical models incorporating construction techniques and requiring tools for modelling excavation and placement of fill. Equipment of this type has been in use for some years, for example the in-flight sand hopper for use with a plane strain box, but there are novel features which will need careful consideration. the experiment proposed will involve measuring the build up of stress in a retaining wall with fill placed behind.

3.9 TEST CONTROL AND DATA AQUISITION SYSTEM

Test control and data aquisition is a necessary requirement for the performance of all model tests; facilities will be common to many users from different Laboratories and therefore should be discussed as a separate topic.

This Section describes a conceptual test control and data acquisition system to permit model test control, condition, process and publish test data arising from the centrifuge tests described in the main report. The initial embodiment of this system is sufficient to demonstrate the basic capabilities of the centrifuge facility.

3.9.1 Conceptual Test Control and Data Acquisition System

The conceptual test control and data acquistion (TC & DA) system should comprise of proven readily-available hardware and software. Development of new hardware and software should be minimised while ensuring maximum system performance. Adopting this stratgey, the TC & DA system should prove reliable and capable of future enhancement.

The conceptual TC & DA system, depicted in Figure 1, is versatile due to its modular construction. The system shown is capable of acquiring data from static, earthquake and dynamic centrifuge model tests, and control of cold-regions, environmental and other data acquisition requirements.

The system also includes the highways required for a video monitoring system and for DC and AC power distribution. The TC & DA system modules, depicted in Figure 1, are described below. The system modules are described in the text from left to right in Figure 1. Control and power lines to the centrally-mounted modules have been omitted from Figure 1 for clarity.

3.9.2 Transducers & Interface Boxes

Practically any type of electronic transducer can be connected to the TC & DA system. Transducers normally used include pore pressure transducers, linearly variable displacement transducers, linear and rotary potentiometers, strain-gauge bridges, force cells, thermisitors, thermocouples, accelerometers and resitivity probes.

Up to 24 transducers are connected to an interface box mounted on the test package. All connectors used in the TC & DA system should be of the military standard bayonet lock type. The interface box contains the necessary circuitry to energise the individual transducers and condition their outputs to low-impedance, high-level analogue voltages for onward transmission. Conditioning the transducers close to source increases the signal to noise ratio of the transmission and simplifies the signal conditioning requirements in the rest of the system. The interface box also permits the performance of the transducers to be verified during test package assembly before the package is placed on the centrifuge swing using the trolley mounted system.

The standard signal conditioning modules inside the interface box should be

instrumentation amplifiers with high common mode rejection ratio. Each amplifier should have selectable decade gains and low-pass analogue filters. These amplifiers are suitable for conditioning outputs from resitive transducers, such as Wheatstone bridges and thermisitors. Dedicated signal conditioning modules are normally required for "non-resistive" type transducers, such as thermocouples and charge-devices. These dedicated modules should either replace an amplifier module, or complement it via a daisy-chain connection to the interface box. This daisy-chain connection can also be used to connect transducers with multiple outputs, such as an array of force cells, to the interface box.

Figure 1 shows three interface boxes, IB1 to IB3 connected to an assortment of transducers. An example of a special conditioning box, CB1 is shown daisy chained to interface box IB1. It is conceived that interface boxes IB1 and IB2 should each interface 24 transducers to the TC & DA system. These 48 transducer outputs can each have an analogue bandwidth up to about 50kHz. The two interface boxes are connected to a termination panel, TP1 using individually-shielded twisted pair cables.

Interface box IB3 and its associated conditioning is intended for up to 16 high-speed analogue outputs with analogue bandwidths upto 10MHz. Interface box IB3 may be connected to the termination panel using shielded coaxial cables.

3.9.3 Termination Panels & Arm Wiring

Two termination panels should be mounted to the swinging platform, one on either side close to the platform supports. Termination panel TP1 is used to interface the signal, control and video lines to the TC & DA system. Termination panel TP2 interfaces the AC and DC user power lines. This panel should also include connections to the user's hydraulic and pneumatic lines.

Maximum seperation should be maintained between the termination panels and their associated wiring to minimise pick-up on the signal and control lines. The data highways for channels 1 to 48 (interface boxes IB1 & IB2) should comprise of individually shielded twisted pair cables. This cabling should also include the control lines. The data highway for channels 49 to 64 (interface box IB3) and the video lines should comprise of shielded coaxial cables.

If possible, the cable runs down the centrifuge arm should be on the outside of the centrifuge booms, to permit a clear line of sight from the arm centre to the test package. This line of sight may be required for centrally mounted devices such as fast-framing cameras, cannons and high-capacity water feed pipes. The cable runs should be easily accessible, so that additional dedicated cabling, such as between a servo motor and power amplifier, can be readily mounted and removed.

3.9.4 Distribution Panels

The signals from, and power supplies to, the swinging platform should be interfaced to the centrally-mounted systems via 3 distribution panels, VD, DD

and PD. Each of these panels and the other centrally-mounted systems should be mounted in ruggedised 19" racking systems mounted close to the axis of the centrifuge. Other fixing points will be required in the central area for future developments.

These systems will be subjected to about 60g under g-max conditions and should contain no moving parts. The chassis with the racking system should therefore be rugged, and perhaps be similar to those used in automotive crash testing.

The video distribution panel VD transmits the video signals from the test package to the video multiplexor, and energises the video devices from the user's transducer power supply PSU.

The data distribution panel DD interfaces the 64 channels of data to the four data acquistion systems the control interface CI1, auxillary outputs and the user's transducer power supply PSU.

The power distribution panel should be remote from the other two panels, and interfaces the user's DC and AC power lines.

3.9.5 Multi-channel Data Acquisition

The multi-channel data acquisition system consists of 64 channels of signal conditioning SC1, an analogue to digital convertor AD1 controlled by a microprocessor uP1 with a test control capability DA1 connected to the control interface CI1.

The signal conditioning module SC1 should contain binary gain amplifiers to complement the decade gain amplifiers in the interface boxes, to optimise the range of the analogue input to the a/d convertor. SC1 should not permit signal offsets to ensure absolute transducer responses are recorded. Additional features might include anti-alias filters. It would be advantageous to change the settings of SC1 remotely.

The inputs should be multiplexed to a analogue-digital convertor AD1, which should be capable of a throughput of 20 samples/second/channel from 64 channels. The AD1 is controlled by a microprocessor uP1. This microprocessor may be a 486 PC, or an IEEE device. If a PC is used, solid-state RAM should be used to emulate floppy and hard disc drives.

The microprocessor is controlled via the sliprings. If a PC is used, it should be possible to use commercially available data acquistion hardware and software, such as Burr-Brown PCI cards and Labtech Notebook software respectively, with apparent local control of the PC. The keyboard input to the PC can be redirected through the serial port. The serial port permits comunication through the sliprings (either optical or signal) with a computer PC1 located in the control room. The colour VGA output from the PC can be converted, using VC1, into a video format such as PAL and then transmitted to a video monitor, M1 located in the control room adjacent to the computer PC1.

If an IEEE device is used, similar to the HBM UPM 100 multipoint measuring unit used on the LCPC Acutronic 680 centrifuge, the microprocessor uP1 could be controlled via the IEEE bus and the optical slipings.

The multi-channel data acquisition system also permits test control via DA1 which can provide analogue and digital outputs to the control interface CI1.

3.9.6 Earthquake Data Acquisition

The earthquake data acquisition system consists of 32 channels of signal conditioning SC2, an analogue to digital convertor AD2 controlled by a microprocessor uP2.

The signal conditioning module SC2 should contain binary gain amplifiers to complement the decade gain amplifiers in the interface boxes, to optimise the range of the analogue input to the a/d convertor. SC2 should include signal offsets to permit transient transducer responses to be recorded. Additional features might include anti-alias filters (such as Laplace Instruments 16 channel PC techfilter card) and simultaneous sample and hold circuitry. It would be advantageous to change the settings of SC2 remotely.

The inputs should be multiplexed to a analogue-digital convertor AD2, which should be capable of a throughput of 10 kilosamples/second/channel from 32 channels. The AD2 should include external triggering capabilities. The AD2 is controlled by a microprocessor uP2. This microprocessor may be a 486 PC, or an IEEE device and controlled through the sliprings.

If a PC is used, it should be possible to use commercially available data acquisition hardware and software, such as Data Translation's DT2831-G card and their Global Lab software respectively. No suitable IEEE devices have been sourced.

3.9.7 High-speed Data Acquisition

The high-speed data acquisition system consists of 16 channels of signal conditioning SC3, an analogue to digital convertor AD3 controlled by a microprocessor uP3.

In a blast test, the system should be capable of detecting arrival times and peak pressures. The system is complemented by the earthquake system which can be used to detect plastic damage and subsequent dissipation of the blast effects.

The signal conditioning module SC3 should contain binary gain high-bandwidth amplifiers, to optimise the range of the analogue input to the a/d convertor. SC3 should include signal offsets to permit transient transducer responses to be recorded. Additional features should include simultaneous sample and hold circuitry. It would be advantageous to change the settings of SC3 remotely.

The inputs should be multiplexed to a analogue-digital convertor AD3, which

should be capable of aggregate megasampling rates per second from 16 channels. The AD3 should include external triggering capabilities. The AD3 is controlled by a microprocessor uP3. This microprocessor may be a 486 PC or another device and controlled through the sliprings.

If a PC is used, it is possible to use commercially available data acquisition products with lower specifications, such as Strawberry Tree's Flash-12 16-channel 1MHz card, Metrabyte's new DAS58 & SSH58 8-channel 1MHz cards with their Viewdac software. Data Translation's new DT2839 32 channel 1MHz card, or Laplace Instruments 8 channel EISA 2.6 Msample/sec card. No suitable IEEE devices have been sourced.

3.9.8 Manual Data Logging

The manual data logging system enables the user to maintain close contact with the test package and verify transducer responses logged by the above three logging systems. Transducer failure and transducer inputs outside the range of the ADC are common place during a centrifuge model test.

The 64 channels are connected through DD to a data multiplexor DM1. This multiplexor is controlled from a manual switch in the control room, via the signal sliprings. The multiplexor output is transmitted to a digital volt meter DVM in the control room.

3.9.9 Test Control

Basic test control is permitted via the control interface CI1. A limited number of selected channel outputs can be directed through the control interface, to permit continuous monitoring of selected channels. These channels can also be used for closed-loop test control.

Control lines are presented in termination panel TP1 from the control interface. These control lines can be from a variety of sources including the multi-channel data acquisition system or the control interface CI2 in the control room. These control lines would typically be used to control a multiplexor inside an interface box for resitivity measurement.

Sophisticated closed loop control, such as between servo-motors and power amplifiers, will require other dedicated test control systems.

3.9.10 Video Monitoring

The video output from the video distribution panel may be connected via a video time-division video multiplexor system to the video sliprings. Currently, the cost of video mulitplexing is expensive. It may be more appropriate to increase the number and bandwidth of the video slipring channels.

The video signals, such as from CCD cameras, are monitored by devices V1 to V3, such as television monitors and video recorders. The video sliprings may also be used to transmit video information from the on-board micro-processors.

3.9.11 Power Supplies

The user will require access to DC, single phase AC and three phase AC power on the centrifuge arm at the test package and in the centre of the centrifuge.

The user power sliprings UPS should be capable of being easily reconfigured using the power interfaces PI1 and PI2, to provide different combinations of electrical power dependant on the type of test being undertaken.

The transducer power supply PSU may comprise of a number of different DC power rails dependant on the types of transducers being used. Electrical power is switched remotely to the arm end using solid-state relays located in the power control interface PCI.

The user power sliprings have insufficient capacity for high power requirements. User access should be sought to the dedicated high-power sliprings used as part of the inflight balancing system.

3.9.12 Video Sliprings

It is recommended to increase the number of video channels offered in Acutronic proposal PD-9530D page 18 to 4. Eight channels may be required if video multiplexing is not adopted.

3.9.13 Optical Sliprings

It is recommended that the fibre-optic rotray joint option offered in Acutronic proposal PD-9530D page 6 is accepted, and that the number of optical passage rotary joints is increased from 1 to 4. This 4 joint passage has been incoporated in the Acutronic 680 centrifuge for Takenaka, Japan, and can be configured, for example, to allow an IEEE bus and 8 full duplex simultaneous RS232 buses.

3.9.14 Signal sliprings

It is recommended to increase the number of signal lines offered in Acutronic proposal PD-9530D page 18 from 46 to 64. These channels should be wired in individually shielded twisted pairs.

3.9.15 User power sliprings

It is recommended to accept the 12 5A power lines offered in Acutronic proposal PD-9530D page 18, provided that access is permitted to dedicated high-power sliprings.

3.9.16 Trolley-mounted System

The trolley mounted system is depicted to the right hand side of Figure 2. The trolley mounted system is used with an interface box to verify the performance of the transducers during test package assembly before the package is placed on the centrifuge swing. The system can also be used to monitor and control tests

conducted on the laboratory floor.

The trolley mounted system is mobile, and comprises of a data distribution panel DD2. This panel is connected to a digital volt meter and signal conditioning SC4, analogue to digital convertor AD4, and test control interface DA4, similar to those described in Section 3.9.5. The analogue to digital convertor AD5 is similar to that described in Section 3.9.6.

3.9.17 Data Analysis & Reporting

Data reduction, analysis & reporting can be performed initially using a 486 PC connected to a postscript laserprinter located in the control room. The 486 PC should be provided with an integrated suite of data analysis, graphical and word processing software, such as Lotus 123, Freelance Graphics and Ami-Pro.

Data reduction, analysis & reporting capability for earthquake data is provided in the Global Lab software provided as part of the trolley mounted system.

3.9.18 Initial Test Control & Data Acquisition System

The conceptual TC & DA system will evolve as the centrifuge facility develops. An initial basic system has be defined (as shown in Figure 2) as a starting point for the commissioning of capabilities. This is a 24-channel system with an analogue bandwidth per channel of about 50kHz. It will have limited application for earthquake and blast models, with some restrictions, for example in the number of channels and on the offsets and scaling capabilities. The system would not be suitable for high-speed requirements.

The initial system provides a capability to measure pore pressures and displacements in a model in flight. There are various factors which must be considered carefully, including the length of cable run from the slip ring stack to the control room and the necessity of providing the capability for future upgrades and development of the system. The initial system proposed here is considered to be appropriate to the demonstration of initial capabilities and will provide a strong base from which to expand the future development of the data aquisition and test control systems.

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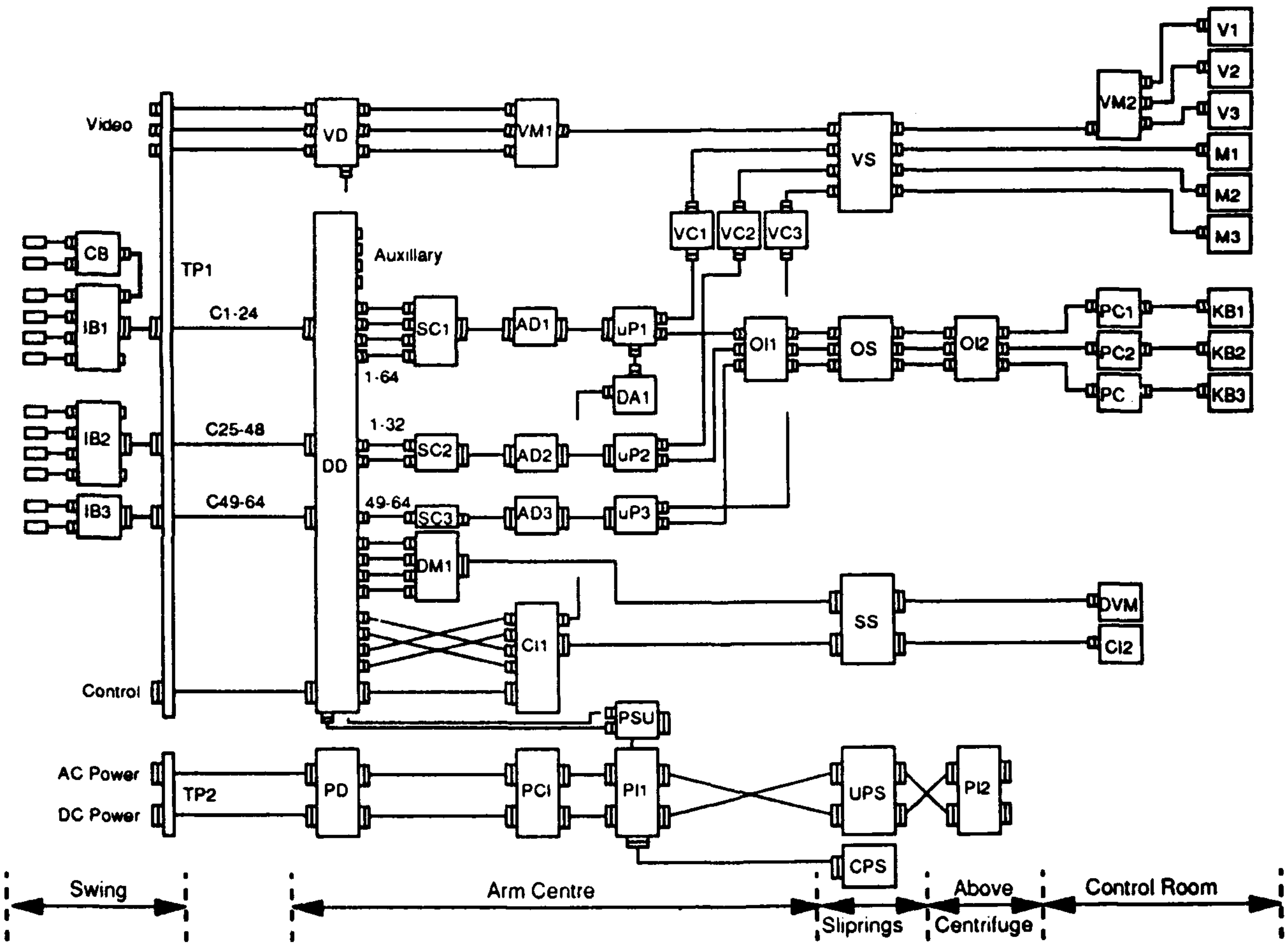


Fig. 1 Conceptual Test Control & Data Acquisition System

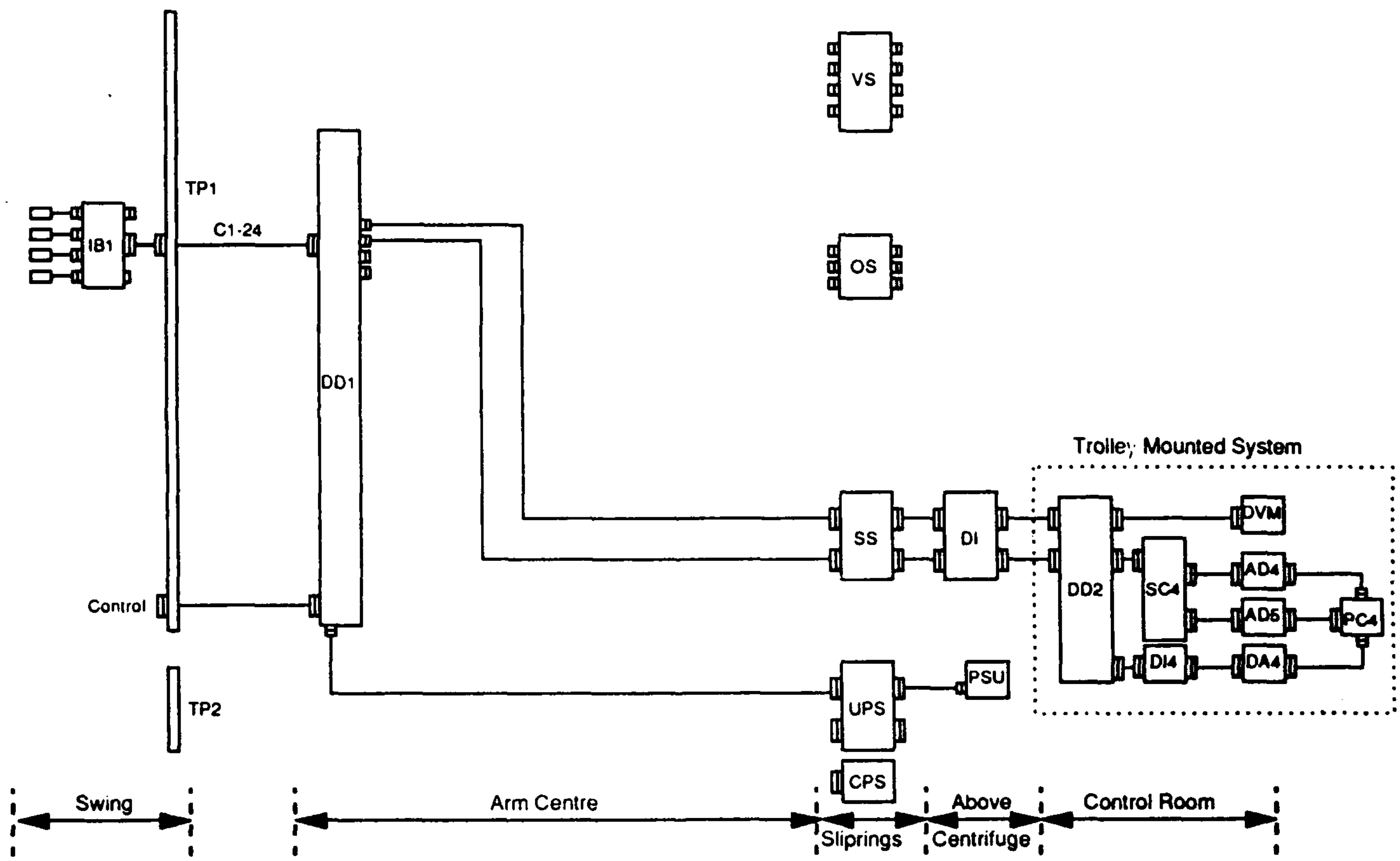


Fig. 2 Initial Test Control & Data Acquisition System

APPENDIX A

COST ESTIMATES FOR EQUIPMENT ITEMS

Equipment items which will be required for the achievement of capabilities on the WES centrifuge are detailed below, together with preliminary costings for their supply and delivery. Although several items can be specified in detail many are considered to be items that will require development and detailed specification prior to order. This is because of both the increased specification of the Acutronic centrifuge that is on order in comparison to ANS&A's original March 1989 response to the BAA, and also because of the wide range of new fields for which equipment is being sought to establish a unique capability at WES.

Many of the equipment 'kits' identified in this report comprise several deliverables, which have been lumped into separate 'Items' for ease of identification. A single 'Item' therefore, might include equipment ranging from instrumentation to mechanical actuators. Thus an earthquake box should also include a junction box with signal conditioning suitable for accelerometers. Such a unit would be unlikely to be required prior to the commissioning of the earthquake box itself. The twelve equipment Items are described in detail in Section 2.1 of this report. Estimated costs for these items are given below, based on an exchange rate of 1.9 US$/UK£. These estimates are for the cost per item ex-Cambridge, including estimated fees for Ciel but excluding shipping and commissioning costs. For several of the Items it will be appropriate to request that the quotation from Ciel be broken down to identify each deliverable.

EQUIPMENT	Budget Cost ('000 $)
Item 1 CYLINDRICAL TUB	70

Cylindrical tub of 1.2 m diameter to contain saturated soil at 350g, with tub extension, single point sand pouring hopper, with sealed lid providing for air pressure and vacuum control.

Item 2 BASIC DATA AQUISITION AND CONTROL SYSTEM	90

Trolley mounted test control and data aquisition system comprising 24 channels with analogue bandwidth per channel of about 50 kHz, data interface, DC power supply, data distribution panel, interface box, appropriate cabling, 486 PC with laserprinter and appropriate software, pore

pressure and displacement transducers and appropriate connectors.

Item 3 IN-FLIGHT CONE PENETROMETER 95

Cone penetrometer drive system and instrumented probe, for use in-flight to measure tip resistance and total force due to sleeve friction and tip resistance in soil deposit, plus piezotip.

Item 4 BASIC LOADING SYSTEM (performance to be confirmed) 155

Basic loading system for general application, with appropriate load cells.

Item 5 BLAST CHAMBER 60

Blast chamber for use inside 1.2 m diameter tub, with torospherical ends and flat base plate.

Item 6 EARTHQUAKE ACTUATOR (performance to be confirmed) 115

Earthquake box comprising spring actuator, strap suspension, equivalent shear beam soil container, transducers with appropriate connectors and signal processing interface box.

Item 7 DOWNWARD HYDRAULIC GRADIENT CONSOLIDOMETER 135

Downward hydraulic gradient consolidometer for circular tub, extension and system for extraction of clay specimen from circular tub.

Item 8 PLANE STRAIN BOX 165

Plane strain box, without windows, with vacuum seal and adaptors for use with the downward hydraulic gradient consolidometer.

Item 9 IN-FLIGHT CONSTRUCTION TOOLS 135

Hydraulic and pneumatic systems to model excavation and surcharge, in-flight sand hopper for use with plane strain box.

Item 10 THERMAL CONTROL SYSTEM

Design study by ANS&A for constant temperature and temperature gradient control system based on thermal barriers both external to and within model containers, with sources of heating and refrigeration and a system of

temperature sensors and control for use in long duration tests.

Item 11 ENVIRONMENTAL CONTROL SYSTEM

Design study by ANS&A for electrically and chemically inert liners and electrical and chemical probes, for control and monitoring of the environment external to and within model containers in long duration tests.

Item 12 WATER-FLOW SYSTEM

Design study by ANS&A for high capacity underslung water flow system to transfer water from sources near the central axis to the platform, stilling tank and flume for mounting on the platform, water level and local flow measurement, and stored angular momentum wave generator.

APPENDIX B

EARTHQUAKE CENTRIFUGE MODELLING: A GENERAL REVIEW OF EQUIPMENT DEVELOPMENT

APPENDIX B: CONTENTS

B1.0 Background

The study of seismic related geotechnical engineering problems has been one of the priorities for many of the centrifuge facilities. Earthquake effects on soil structures are complicated and earthquake centrifuge modelling has proved to be a useful tool in the research. There are three key equipments in earthquake centrifuge modelling i.e. earthquake actuator, suspension system and model containment. There has been a wide range of development in these areas in recent years and different approaches has been adopted at different places. When developing earthquake modelling capability on a specific centrifuge decisions have to be made to choose one type of equipment or another. Important factors that need to be considered are the cost and risk involved in development, the quality of input motion and the maintenance. This appendix will review the current status and the development of equipment in earthquake centrifuge modelling.

B2.0 Earthquake Actuator

Researchers at a number of centrifuge centres have developed the facilities for earthquake centrifuge modelling, however there is a wide range of differences between these facilities. There is controversy over the ideal type of system, the preferred class of input to a model, and the cost involved in fabrication and operation. The scaling relationship for centrifuge modelling requires the frequency of vibration in the model to be increased by N times where N is the centrifugal acceleration factor. The dominant frequencies of a typical earthquake in the field may range between 0.2Hz to 5Hz and, supposing a centrifuge acceleration of 100g, that requires the actuator on a centrifuge to be able to generate a model earthquake with frequencies between 20Hz to 500Hz. As the earthquake acceleration is also increased by N times, it requires a large force at a high frequency from an actuator even if the shaking mass is just moderate. In terms of of energy needed from the actuator, the motor needs to have the capability to reach a high power output in a instant and have a good control. That would involve considerable complexity in the design of mechanical system and control system. Generally one has to consider three aspects in making the decision of which types of earthquake actuator to choose i.e. a) cost of making and running; b) simplicity in testing and maintenance; c) and adjustability in earthquake input.

A specification was proposed by Cheney et al (1983) for an "ideal" earthquake actuator which might go aboard a large centrifuge. It would have the capability to perform a wide range of experiments at a scale large enough to model important aspects of typical foundations and earth structures. They summarized three key requirements for such a shaker: a) a shaking area of 3ft x 1.5ft and a minimum payload of 600 lbs; b) shaking predominantly in the prototype-horizontal direction; and c) shaking characteristic specified by an "ideal" response spectrum over frequency range from 0.2Hz to 5Hz in prototype scale, the centrifuge acceleration factor ranging from 20 to 100, and the response spectrum anchored at peak acceleration between 0.05g and 0.6g in prototype scale. The second key feature in this specification has been generally accepted by researchers as a consensus in the design of earthquake actuator. However there are considerable arguments about the other two especially the third one.

Firstly such an "ideal" earthquake does not necessarily represent the real situation in the field. Although it is based on the recording of one or two past earthquakes, there have not been any two earthquakes in the past that had identical ground motions. Therefore it

may be regarded as a real earthquake in the past but it does not follow that a future earthquake at a different location and in many case at the same location will be like the "ideal" earthquake.

Secondly, the complexity in the input motion may make it difficult to identify some key aspects of behaviour of an earth structure and if one is studying the influence of some controlling parameters, using a relatively simple sinusoidal input will help to understand some fundamental mechanisms of dynamic response of an earth structure. A simple sinusoidal input also is realistic. In the field the recording of vibration on soft ground repeatedly shows this type of earthquake motion. Examples have been the Mexico Earthquake in 1986 and the Loma Prieta Earthquake in 1989. This type of earthquake motion has usually been most devastating.

Thirdly one has to take account of the large increase of cost needed in order to have an actuator which can generate this type of "ideal" input motion.

There are many types of earthquake actuators being used on centrifuges throughout the geotechnical engineering community and there can be various ways to categorize them. Earthquake excitation is primarily about energy. From the point of view of how the shaking energy is provided, the earthquake actuators can be divided into 5 main categories: mechanical, piezoelectric, explosive, electromagnetic and hydraulic.

B2.1 Mechanical Shaker

A mechanical shaker obtains the energy for shaking from a mechanical system such as springs, or rotating cams, or the stored kinetic energy of the rotation of a centrifuge. Generally speaking a mechanical shaker has the advantage of relatively low cost in manufacture and maintenance, being easy to operate and being capable of generating sinusoidal vibration at a range of frequencies. One difficulty with a mechanical shaker is to control the input motion accurately. It is also difficult to generate input motions which have the response spectrum of a wide band of frequencies. There are a number of mechanical shakers in operation or under design on centrifuges at different research centres. The following are a few of the documented examples.

B2.1.1 Spring-Actuated Shaker Developed by Morris

The simplest and the earliest shaking system ever used on the Cambridge 10 metre beam centrifuge was the earthquake actuator developed by Morris (1979). The energy of excitation was provided by a reaction mass which was connected through a spring system to the shaking plate on which the model container was mounted. The spring was primed and then released in flight, generating a single frequency sinusoidal motion which decayed gradually with time. A sketch of the system is shown in Fig. B1. The system was successfully used by Morris to study the seismic response of rocking towers on a sand bed. A typical earthquake input is shown in Fig. B2. Some valuable data were captured during the tests. However the system was soon phased out due to the introduction of the Bumpy Road Actuator, which has the capability of multiple events.

The most obvious advantage of the Morris system is the simplicity in concept and operation. Energy is stored in a spring and reaction mass and thus some important characteristics of input motion such as the amplitude and frequency

can be pre-set by controlling the combination of the spring stiffness, mass of model and reaction mass. The whole system works as an independent robust unit and hence make the maintenance and transportation easy. The motion it generated has a clear trace of a typical single frequency sinusoidal wave and is very consistent.

This mechanical system has the disadvantage of lack of versatility mainly due to its simplicity in its control system. Firstly, the profile of the input motion is not entirely satisfactory because the first peak is the largest and it takes quite a number of cycles before the vibration stops. Secondly the triggering system is a mechanically loaded and there is not enough space to locate auto-control devices. Therefore the system cannot be reload it during flight. It is a one shot system. Thirdly the operational procedure is not satisfactory for safety as the snap catch is set by hand, which when fully loaded has a dangerous level of stress and energy.

B2.1.2 Other Spring-Actuated Systems

Because of the simplicity in concept and the relatively low cost in fabrication and maintenance spring-actuated shaking systems have been adopted by on other centrifuges, for example, on the Genisco Centrifuge at Caltech, Ortiz et al. (1983). In this case the centrifuge itself was used as the reaction mass, Fig. B3. The system could generate one or two cycles of shaking. Research work using this facility included a study of seismic response of model cantilever walls. Its advantages and disadvantages are very similar to those of the Morris system.

B2.1.3 Bumpy Road Actuator

The most successful earthquake actuator by far in terms of experience of research and the number of earthquakes that has been generated is undoubtedly the Bumpy Road Actuator at Cambridge University. The basic principle of the system involves a track with the desired wave form mounted over about a third of the circumferential length of the wall of the pit housing the centrifuge. A sketch of the actuator is shown in Fig. B4. To fire an earthquake a wheel on the end of the centrifuge arm is quickly pushed outwards so that it will encounter and move along the track. The inward-and-outward motion of the wheel is translated into circumferential back-and-forth motion of a model container at the end of the centrifuge arm by a lever arrangement. A typical input motion generated by the Bumpy Road Actuator is shown in Fig. B5. The system was commissioned in 1980 with cost shared between US. National Science Foundation and Cambridge University. Schofield (1981) discussed in some detail its design and operation and the system was fully reported in the thesis of Kutter (1982). Since then extensive research work has been carried out using this unique system. Up to date more than 1300 earthquake events have been recorded on a wide range of models including piles, shallow foundations, sand beds, rocking towers, slopes, retaining walls, dykes, embankments, artificial islands, etc. A large data archive has been created and the data have been used to help design, to assess and develop engineering calculations and to validate numerical calculations. The work using Bumpy Road Actuator has formed the basis of of ten Ph.D Theses alone of the Cambridge Soils Group.

The Bumpy Road System is well known and has been extremely successful. Research work based on the Bumpy Road has been widely published. One particular feature of the system compared with other simple mechanical shakers is its capability of generating multiple events during one flight. Wear on critical bearings means that the amplitude of a model earthquake on a new flight cannot be precisely predicted but it is normal practice on the Bumpy Road to apply a series of model earthquakes with different amplitudes to the same soil model anyway so as to study the response of the model to successive events. The input motion is broadly a single frequency sinusoidal vibration with varying amplitude for different cycles. The profile of the acceleration is simple but quite satisfactory. The input motion is very consistent at specific testing accelerations and the control system is comparatively simple. There is potential flexibility in controlling the duration and frequency of a model earthquake by changing the testing centrifuge acceleration or changing the track fixed on the chamber. However a change of track involves considerable physical effort and can take several days.

This type of facility is probably only suitable to the Cambridge 10 metre beam centrifuge and its chamber. The whole system is not an independent unit (which can be loaded on and off a swing) and hence many days are lost in "changeover" time and this constrains use of the centrifuge itself. The lever mechanism for controlling earthquake amplitude need frequent maintenance to achieve consistency in input motion.

To transfer effectively the vibration of the wheel to the model container the strongbox has to be in firm touch with the face plate. Therefore it is difficult to test at low centrifuge acceleration. At high g level because of high frequency in model earthquake only a small displacement is required to generate a motion of moderate amplitude. That is difficult to achieve by such a mechanical system. The dynamic response of the system also needs to be considered carefully, to avoid possible resonance during operation.

The system has achieved outstanding success and has been operated productively for more than 12 years now.

B2.1.4 Hammer Plate Shaker

A very simple hammer plate exciter was developed and used at Princeton University in the mid 1980s, Coe et al. (1985). The principle of the system is shown in Fig. B6. To actuate an earthquake a hydraulic hammer will strike a base plate which moves in horizontal direction, generating vertically propagated waves. The principle is very simple and can be used in calibrating a control and data acquisition system or in some cases to measure dynamic properties of soil and soil structures. But the input motion is far from desirable. The impact loading on the base plate may cause strain concentration and indeed may even create a failure zone of soil. The usefulness of this system is limited.

B2.1.5 Eccentric Cam Shaker

The principle of this type of shaking system is use the kinetic energy stored in a rotating eccentric cam mechanism. One such system was developed at Tokyo

Institute of Technology to study whether the centrifuge was capable of taking vibrations, Kimura et al. (1988). The cam shaft was driven by a high-power print motor installed under a centrifuge model container, Fig. B7. Typical input motions that it generated are shown in Fig. B8. The advantage of this shaker is the cost for building it. The repetition of tests is extremely easy. It is a very economic solution to providing a basic shaker. But the motion it can generate is highly restricted. It can be used in some initial study about the dynamic behaviour of a centrifuge and may also used in some simple tests. Its potential use in highly demanding research is unlikely.

B2.1.6 Oscillating Link

An oscillating link shaker was developed at Cambridge University in the late 1980's. A general setup of the system is shown in Fig. B9. The vibration is generated by 1.1 kW induction motor. It can provide sustained low frequency cycling and also high frequency earthquake excitation. The facility was proof tested on the Acutronic 661 Centrifuge at City University, Ford et al. (1989), and also tested on the beam centrifuge at Cambridge. A typical input motion is shown in Fig. B10, which is approximately a single frequency sinusoidal vibration.

The system has good control of amplitude and duration of the input motion. The frequency of the excitation can also be preset. It is possible to generate multiple events during one flight. The shaker can be operated as an independent unit. The system is quite simple and the cost is relatively low.

One major difficulty is that the link was highly stressed in the initial design. Also a large amount of energy storage is difficult to achieve. As the frequency of a model earthquake is increased by N times and thus very high it requires the motor to deliver peak power instantaneously. Therefore the payload allowable is limited. In the initial development stage an electrical motor was used but the energy needed can be supplied by a hydraulic motor with energy accumulating system. The main problem about the input motion is to keep the excitation in straight horizontal direction - vibration force is applied through the contact link, which is likely to cause torsional response especially if the centre of gravity of the payload is not on the line of the link.

This system remains attractive because of low cost and flexibility in input motion. Further improvement is possible if it is necessary.

B2.1.7 Cambridge 1992 Spring-Actuated System

A new spring-actuated system is being developed at Cambridge in 1992. The principle of the shaker is shown in Fig. B11. The main components of the system include a shaking platform, an actuating spring and mass, a slave spring and mass, a break and a ESB (equivalent-shear-beam) container. The actuating spring can be pre-loaded and thus stored the energy needed for excitation. To fire an earthquake a release mechanism is triggered and the vibration of the actuating spring and actuating mass will excite the vibration of the platform and the slave mass. After a certain period of vibration a break will be imposed on the platform and vibration will stop within a few cycles. Theoretical motion time

history is shown in Fig. B12. The frequency of input motion can be changed by varying the position of the actuating and/or slave mass.

This design has considerable advantages over other mechanical systems. Firstly there is active control over the amplitude, duration and frequencies of the input motion. It appears possible to have several springs and release mechanisms and to have different combinations of amplitude, frequency and phase so that a wide range of earthquakes can be generated. Secondly because the energy for excitation in stored in springs and vibration is self-resonant it is possible to shake a model of considerable size and weight. Thirdly although the input motion is still simple it can have components of two identifiable frequencies. That is very useful in the study resonance due to stiffness deterioration of soil. Fourthly the shaking platform is isolated from the centrifuge itself since it was supported by flexible straps hanging on four supporting columns on the swing. No bearing is required. Lastly this system can be made into a robust independent system which is easy to transport and maintenance.

This system is still at a design stage and needs to be proof tested. More development work is anticipated. Although multiple events are possible in theory it is designed for one event because of limited space available on the platform of the beam centrifuge at Cambridge.

The system has high expectation of success. Yet the cost of fabrication is quite low. The system at Cambridge is design to shake a total weight of soil plus containment of up to 300 kgs.

B2.2 Piezoelectric Shakers

The principle of piezoelectric shaker is to apply an electric field on a piezoelectric ceramic material and that would generate a predictable deformation of the material. A piezoelectrical shaker was developed by Arulanandan et al. (1982) at UC Davis. Fig. B13 is a sketch of the shaker. The shaker is capable of generating sinusoidal excitation at around 500 Hz on a soil sample up to 23 Kg at 100g. The shaker exploited resonances in the driving system which greatly reduced the required output power. It may also be modified to generate a shaking frequency as low as 100 Hz. The main constraint is that the energy available from piezoelectric material is limited. Therefore it is difficult to shake a model even though it is of moderate mass.

B2.3 Explosive Shaker

The energy released by the explosion of a small charge to generate excitation has been used by several researchers in the late 1970's. At the Centre d'Etudes Scientifiques et Techniques de l'Aquitaine in France, Zelikson et al. (1981) studied soil-structure interaction during earthquakes using vibration generated by small explosives as input. Charges of 1 to 5 grams are exploded at the plate at the end of an air blast modification chamber; up to 10 charges may be held by this plate, and may be detonated in any sequence. The pressure of air blast is transferred to the soil by a vertical plate and a membrane. Fig. B14 shows a sketch of the shaker. It is reported that the spectral content of motions generated by this shaker compares favourably with spectral from actual large earthquakes. At about the same time in Cambridge, Morris (1981) used the vibration generated by small quantity of explosives to study the rocking behaviour of tower

structures in centrifuge flight.

One important aspect that needs to be pointed out is that in an earthquake in the field the propagation of seismic vibration is dominated by vertically propagated shear waves while in an explosion and also in the shaker in Fig. B14 propagation of P waves is the major phenomenon. There are fundamental differences between these two types of waves and hence one has to be careful in the interpretation of the data. Also in many laboratories the regular use of explosives would be impractical.

B2.4 Electromagnetic Shaker

The development of an electromagnetic shaker by Shimuzu for the centrifuge at Chuo University in Japan was reported by Fujii (1991). The principle of the system is shown in Fig. B15. The shaker takes energy from an electromegnetic setup which consists of a pair of magnetic coils which are setting face to face with each other with a small gap. Constant direct current is applied to one of magnetic coils while controlled alternative current is applied to the other. The attraction and repulsion generated between the coils will shake the table and the model. The system had a maximum payload of 200 kg and the frequency range is between 50 to 400 Hz. The profile of the base acceleration is sinusoidal. In the system the heavy electro-magnet are permanantly attached to the shaking table. When the earthquake begins it can take upto five cycles before the table oscillates at peak amplitude. The shaking then continues for much longer than it is appropriate for an earthquake. If larger current is used there will be more electrical interference with test data. The maximum earthquake acceleration generated is relatively low.

B2.5 Hydraulic Shaker

In the early 1980's considerable efforts were made in the US and Japan to develop servo-controlled electro-hydraulic systems. A hydraulic shaker obtains the energy for vibration from a hydraulic accumulator and has the capability in theory to provide nominally programmable input motion. The principles and basic design requirements of a electro-hydraulic shaker were outlined by Ketcham et al. (1988). A sketch of the hydraulic shaker at Colorado University is shown in Fig. B16. A large hydraulic shaker is mounted under a shaking table. The mass of the swing basket provides the reaction mass. The direction of motion induced by the actuator is parallel to the axis of the centrifuge itself, reducing the errors which may be introduced by Coriolis effects or, on small radius centrifuges, by the curvature of the centrifuge acceleration field.

The advantage of a hydraulic shaker is the adjustability in its input motion. A typical input motion achieved on the Genisco centrifuge at Caltech is shown in Fig. B17. Hydraulic shakers have been adopted on a number of centrifuges in the US, at places such as Caltech, UC Davis, University of Colorado at Boulder, RPI, Princeton and also in Japan at the Port and Harbour Research Institute, Tokyo Institute of Technology, the Disaster Prevention Research Institute at Kyoto University, etc. In theory it can offer programmable control over the duration and spectrum of an earthquake, although in practice it may be difficult to achieve at high frequencies. It offers the promise for producing "earthquake-like" motion. The system has been successfully used in a number of centrifuges and information and experience is available about the design and operation of this type of system.

The cost of hydraulic shaker development, fabrication, and proof testing is quite high. This type of system has been widely used so far only for a relatively small payload. The ability of servo-valves to response instantly to the flow of large amount of energy has yet to be tested. The control over input motion at high frequency is not satisfactory in some cases. The system is limited by the resonance of the column of oil in the pipe between the valve and actuating piston.

B3.0 Suspension System

When a model earthquake is actuated on a centrifuge, a considerable amount of energy is released during a short period of time. The large vibration force involved could generate substantial impact on a machine if no proper measure is taken to isolate the vibration. If the impact is passed onto the bearings of the centrifuge, this will reduce the life of the facility. With the increase in payload, and in the intensity of earthquakes, the use of an effective suspension system is increasingly more necessary.

B3.1 Flexible Strap Suspension

One effective way of isolating the vibration from the centrifuge is to build the shaker, the model package and the reaction mass as an independent system and the system which is connected by flexible straps to the centrifuge. In the spring-actuated shaker being developed at Cambridge, the actuating system, the model container and the shaking table will be hung on the swing by flexible steel straps, Fig. B11. The whole system is self-contained and minimum impact will be passed on directly to the centrifuge. The arrangement is similar in many respects to that which was successfully used in the Morris system.

B3.2 Rubber Isolation

In the oscillating link shaker developed in Cambridge, the shaker and the model container is isolated from the swing by a thick rubber layer, Fig. B9. Vibration of the shaking system is damped out by the rubber layer. In the proof tests carried out on the beam centrifuge, accelerometers were fixed on the swing and the centrifuge arm to check the effectiveness of the rubber isolation. The results showed that the amplitude of vibration on the swing was less than one third of the input motion. There was hardly any vibration recorded on the arm.

B3.3 Air Bearing

An effective suspension system has used an air bearing to detach a shaking plate from the floor of a centrifuge strongbox. This Acutronic system was installed in Princeton. Details of its fuctioning have not been published.

B4.0 Model Containment

In the field a most important geotechnical problem is associated with a soil stratum of large lateral extent which can be idealized a soil layer of infinite lateral extent. In a centrifuge test a model of earth structure is built inside a model container and thus artificial boundaries are imposed, creating boundary problems or "box effect". These problems have to be carefully addressed in order that a centrifuge test can realistically model the behaviour of the corresponding prototype. The problems related to model

containment were studied in detail recently by Schofield and Zeng (1992). Three major boundary problems may be caused by a model containment, i.e. the problems in stress field, strain field and seismic waves, Figs. B18 - B20. The design criteria of an ideal model containment for earthquake centrifuge modelling are outlined by Schofield and Zeng (1992):

1) The end walls should function as shear beams with the same dynamic stiffness as the adjacent soil, so as to achieve strain similarity and to minimize the interaction between soil and the end walls and hence minimize P waves generated.

2) Each end wall should have the same friction as the adjacent soil so that it can sustain the complimentary shear stresses induced by base shaking and thus the same stress distribution as in the prototype equivalent shear beam can be achieved.

3) The side walls should be frictionless so that no shear stress is induced between the side walls and soil during base shaking to create the same two-dimensional condition as in the prototype.

4) The model containment should be rigid statically to achieve a zero lateral strain Ko condition, and after shaking to maintain its initial size.

5) The frictional end walls should have the same vertical settlement as the soil layer contained during the spin-up of a centrifuge to avoid initial shear stresses on the boundary. Otherwise the normal stress at the base will be affected.

Among the five requirements listed above the first one is most difficult to satisfy since the stiffness of soil is changing during cyclic loading. However even if it is not possible to vary stiffness of end walls during a test, it is possible to design end walls which approximately match the stiffness of soil over working conditions in which the range of stress change is not large. During base shaking the same dynamic shear stiffness means that the end walls should have the same deflection and natural frequency as the soil layer in the model container.

For earthquake centrifuge modelling during the past more than one decade, different types of model containment have been used on individual centrifuges for different specified problems. The following is a summary of design principles and characteristics of several widely used approaches.

B4.1 Rigid Wall Model Container

At the early stage of earthquake centrifuge modelling, no special consideration was given to the model containment. Design requirements for model containers of earthquake tests were just the same as that for static tests - to have enough strength and stiffness. A typical example of this type of model container with rigid side and end walls is shown in Fig. B21.

Although this type of model container is strong and rigid and thus has satisfactory initial stress conditions, such a boundary condition would cause stress and strain dissimilarities, and generate horizontally propagated P waves during base shaking. An experimental and numerical study was reported by Whitman (1988). Contours of peak dynamic shear stress near the rigid end walls show that the effect of a rigid "wall end"

extends to a distance of about twice the depth of the stratum. Therefore for a relatively long model container if the places of interest are located at the centre area of the model it can be assumed that the stresses and deformation of the soil in that area is close to that in the corresponding prototype. But still the influence of P waves has to be addressed. For a short model container and in the case of a long earth structure, the problems caused by smooth rigid end walls can considerably affect the results of a test.

B4.2 Soft Absorbing Boundary - Duxseal

To solve the problem of incident waves being reflected by rigid end walls the concept of an absorbing boundary was introduced. The practice of using an industrial fill material called duxseal at the end walls has been proved to be very effective in reducing the energy reflected from the end walls especially at high frequencies, Coe et al. (1985). A typical boundary setup is shown in Fig. B22. A recent research programme based on the data of model tests shows that such a boundary can absorb two third of the reflecting waves even at 1g condition, Steedman et al. (1990). A detailed study of the mechanical properties of duxseal material is reported by Campbell et al. (1991).

The use of duxseal clearly reduces the influence of incident waves. However it also causes other concerns as the properties of duxseal such as friction and stiffness are difficult to determine in standard laboratory tests especially when working at a high stress level in a centrifuge test. It is also difficult to achieve consistency in the data. It is not known what shear stresses are between the duxseal and the soil body. It is also difficult to find a consistent numerical model for such a boundary so as to carry out theoretical and numerical analysis on the data of model tests. Moreover as duxseal is a relatively soft material such a boundary will deform laterally under the increased lateral pressure during the spin-up of a centrifuge and hence can not satisfy requirement for zero horizontal strain.

B4.3 Rigid Absorbing Boundary

This type of boundary is made of a rigid box containing soft energy absorbing materials. An example of it is the wooden box filled with plastic foam used at Cambridge, Fig. B23, Zeng (1990). In theory this setup could absorb incident waves while satisfying the requirement for zero horizontal strain in soil. But there are no experimental data or analytical results available to quantify the effectiveness of the boundary. Another reason of using this type of boundary setup s to reduce the total weight of the package.

B4.4 Free Slope

Uncertainties about boundary conditions in some end wall setup make numerical calculation difficult. One possible solution was suggested by Finn (1986) by using a free slope at each end, Fig. B24. That would create a clearly defined boundary conditions in numerical modelling. It is most useful in the tests specially designed to generate data for code validation purposes. However it needs to be pointed out that the geometry of the model was chosen to accommodate the finite element representation, rather than to match a specific prototype.

B4.5 MIT Stacked Ring

The concept of a flexible boundary was first adopted by Whitman et al. (1981) in a

stacked circular ring apparatus which was made of separate aluminium rings stacked together, Fig. B25. This type of soil containment has been used to simulate the behaviour of a column of soil within a stratum. Ideally the rings should move with the soil and develop dynamic shear stresses at the soil-ring interface to complement the dynamic shear stresses on horizontal planes through the soil, and prevent extensional strain in horizontal directions. The friction between the rings was reduced so that the rings could move relative to each other, thus creating a flexible boundary.

This first step forward in achieving an ideal boundary condition for dynamic centrifuge modelling still had several unsatisfactory aspects. Firstly as there was no direct control of the lateral stiffness of the apparatus, the relative displacement between the rings under a base shaking could have strain concentration at certain levels of a soil column. The discontinuity in the deformation of the boundary may cause local arching in soil. Secondly the cylindrical container had a smooth inner surface which could not sustain shear stresses and thus there was still distortion in the stress field. Thirdly the circular shape and the relatively low height to length ratio of the model container created a three dimensional problem which was difficult to analyse. It was suggested that a height to diameter ratio of 1:1 is marginal for satisfactory testing; a ratio of 1:2 or less is more desirable.

B4.6 Laminar Box

Many failures of earth structures during earthquakes in the field are caused by liquefaction of saturated soil. To study liquefaction events on a centrifuge a modified version of stacked rings, a laminar box, was proposed and tested by Hushmand et al. (1988) and later by Law et al. (1991). The model containment used at Caltech is shown in Fig. B26. The design principles are outlined by Hushmand et al. (1988). A laminar box consists of rectangular frames stacked together with bearings between the frames to reduce the friction so as to mirror the stiffness of a liquefied soil column. The possible slip of one frame relative to another is supposed to allow for the large displacement associated with liquefaction of saturated soil. The data of centrifuge tests using the box show that it satisfies the requirements for a flexible boundary which is compatible with the behaviour of liquefied sand.

However the end walls still can not sustain complimentary shear stresses and hence the stress condition in the model is not entirely satisfactory. Also the design concept restricted its use to modelling of an event where full liquefaction of a whole soil column is expected. For correct modelling of events prior to liquefaction there must be further improvement in the boundaries. An alternative way of achieving liquefaction at the end of a box would be to have rigid ends, and an upward flow of fluid causing fluidization of the soil near the end walls during the earthquake event.

B4.7 Absorbing and Frictional Boundary

The unsatisfactory stress conditions in a duxseal absorbing boundary leads to the introduction of an absorbing and frictional boundary. Since cyclic shear stresses play a dominant role in the seismic response of a soil layer it is very important that the end walls can sustain shear stresses. A recent study on the effectiveness of an absorbing and frictional end walls was carried out at Cambridge, Madabhushi et al. (1991). The setup of the boundary is shown in Fig. B27. The end walls are constructed using duxseal blocks with thin shear sheets attached as the contacting faces with the soil contained.

The shear sheets were made of aluminium dural sheets coated with sand. Model tests were conducted to study the complementary stresses at the ends and both normal and shear stresses at the base. Some of the transducers used in the test is also shown in Fig. B27. It was concluded that this type of boundary can sustain the complementary shear stresses if the intensity of earthquake is not high. That has led to uniform shear stresses and normal stresses at the base. However when the shaking intensity is high, large complementary shear stresses were generated which exceeded the yielding stress of the shear sheet. The unbalanced complimentary shear stresses caused a cyclic moment, leading to the rocking of the sand layer. The resulting variation in vertical normal stresses along the base were recorded.

This type of boundary can satisfy the requirement of absorbing incident waves and sustaining complimentary shear stresses. The major unsatisfaction is that the deformation condition at the boundary is still unknown, leaving a question about the initial stresses in soil and deformation of the boundary during base shaking.

B4.8 ESB (Equivalent-shear-beam) Model Container

A recent attempt to build an ideal model containment for earthquake centrifuge modelling is reported at Cambridge University, Schofield and Zeng (1992). A new type of model container - an ESB (equivalent-shear-beam) container - has been designed and tested. The model container wall is made of rectangular frames of dural spaced by rubber layers so as to achieve the same dynamic stiffness as the soil it contains. To sustain complementary shear stresses induced by base shaking at each end wall a flexible and inextensible frictional sheet is introduced. A sketch of the model container is shown in Fig. B28. Data of model tests show the end walls had deflection close to the predicted deformation of the soil contained. The acceleration field in the model was uniform and the rocking of the package was small. Therefore the ESB container satisfies most of the requirements of an ideal model container for earthquake centrifuge modelling. This type of model container can be easily adopted by other researchers on their earthquake modelling equipment. The model container is believed to be appropriate for models of working conditions in which well engineered foundations in the field sustains their design earthquakes without liquefaction of the ground, and without large permanent displacement which would destroy the engineering works.

The main limitation of the container is that it is designed to have the same average stiffness as a soil layer in the design earthquake. However the stiffness of soil does change with void ratio, effective stress and shear strain in the soil, and during centrifuge tests the stiffness of the soil will change while the stiffness of the container is fixed. Therefore the box is most appropriate for use in conditions in which the change of soil stiffness is within a certain limited range.

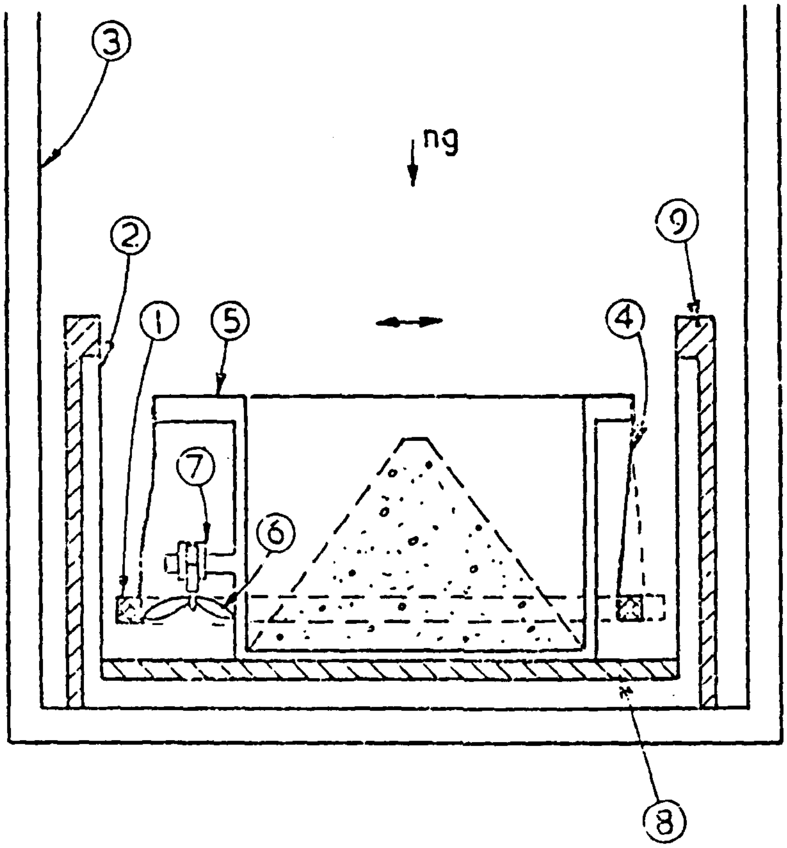
B5.0 Conclusions

There has been considerable progress in the technique of earthquake centrifuge modelling since it was started in late 1970's. The design and testing of earthquake actuator, suspension system and model containment is considered to the critical components in facility development. From the above review of recent development in the three important areas in the equipments for earthquake centrifuge modelling, the following conclusion remarks can be drawn:

1. Different types of earthquake actuators have been designed and installed on geotechnical centrifuges. Each type has its advantages and disadvantages. The two major types are the mechanical and hydraulic shakers. Mechanical shakers cost much less to fabricate and can be designed to generate mainly sinusoidal type input motion. Hydraulic shakers are expensive to develop but can have more flexibility in controlling input motion. When making decision on what type of shaker is suitable for a specific centrifuge, one has to consider the cost of installation, the complexity of operation and maintenance, the adjustability in input motion and the possible risks that may be involved.

2. The suspension system is very important in the design of a shaking system. A properly designed suspension system can isolate the vibration of the shaking system from the arm of centrifuge. Otherwise the impact on the machine can reduce the time expectance of utility especially when a system has a large payload.

3. Model containment has to be designed and constructed properly in order to reduce the effect of the artificial boundary condition imposed on a soil model. In earthquake tests special concerns should be given to the stress and strain conditions near the boundary and the seismic waves generated. Different approaches have been adopted by researchers. It seems that the equivalent-shear-beam container has so far given the most desirable results.



1 reaction mass
2 flexible strips
3 centrifuge arm
4 springs
5 soil container
6 catch pieces
7 minature jacks
8 underlying decking

Fig. B1 The spring-actuated shaker developed by Morris

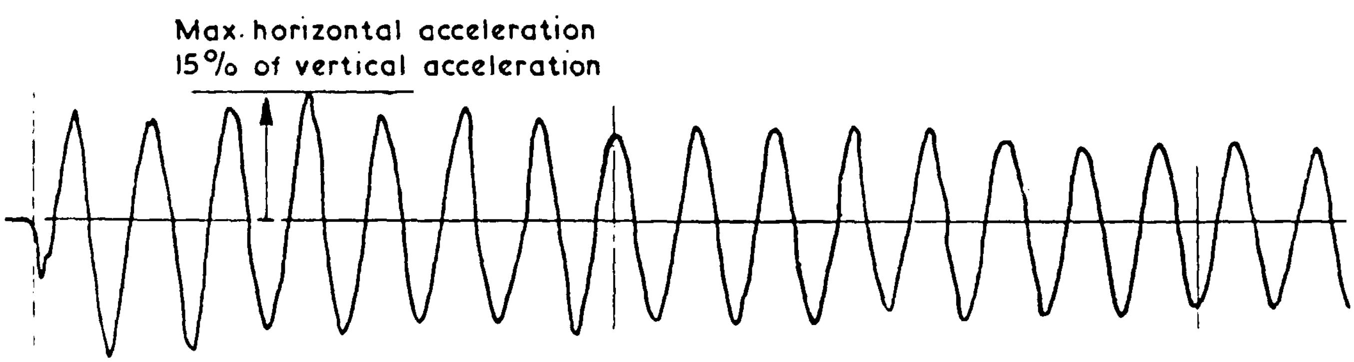


Fig. B2 Typical input motion generated by the Morris shaker

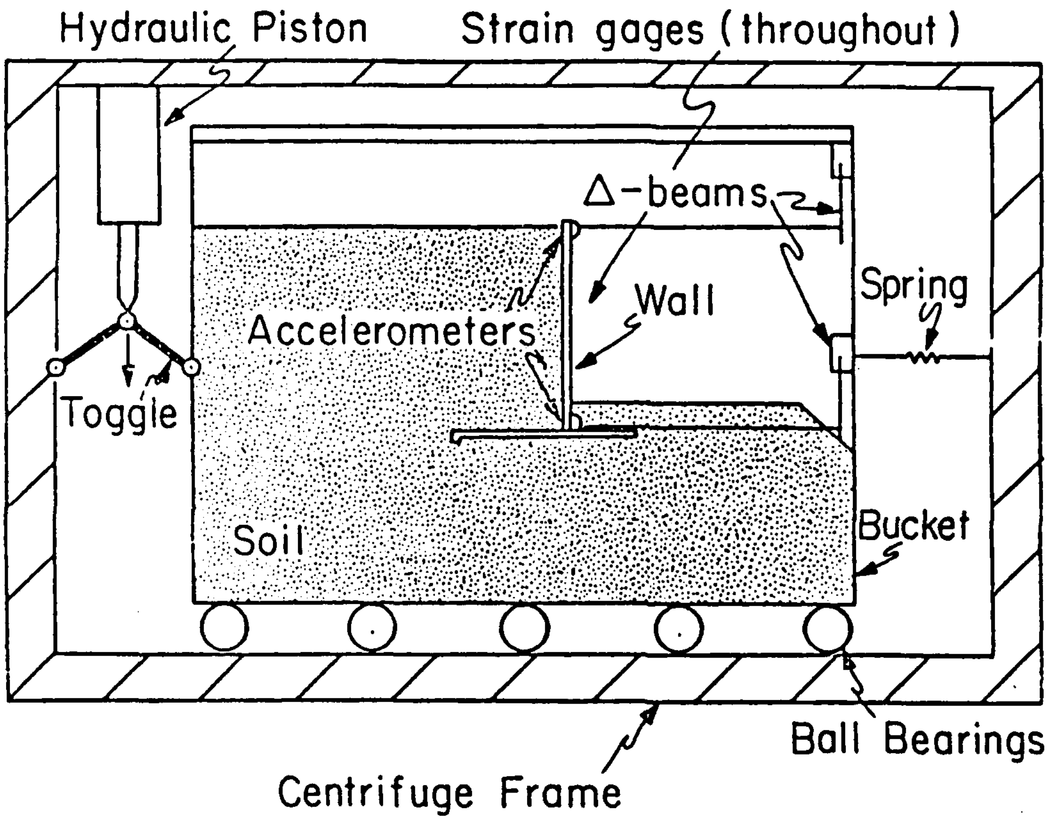


Fig. B3 The spring-actuated shaker at Caltech, Ortiz et al.

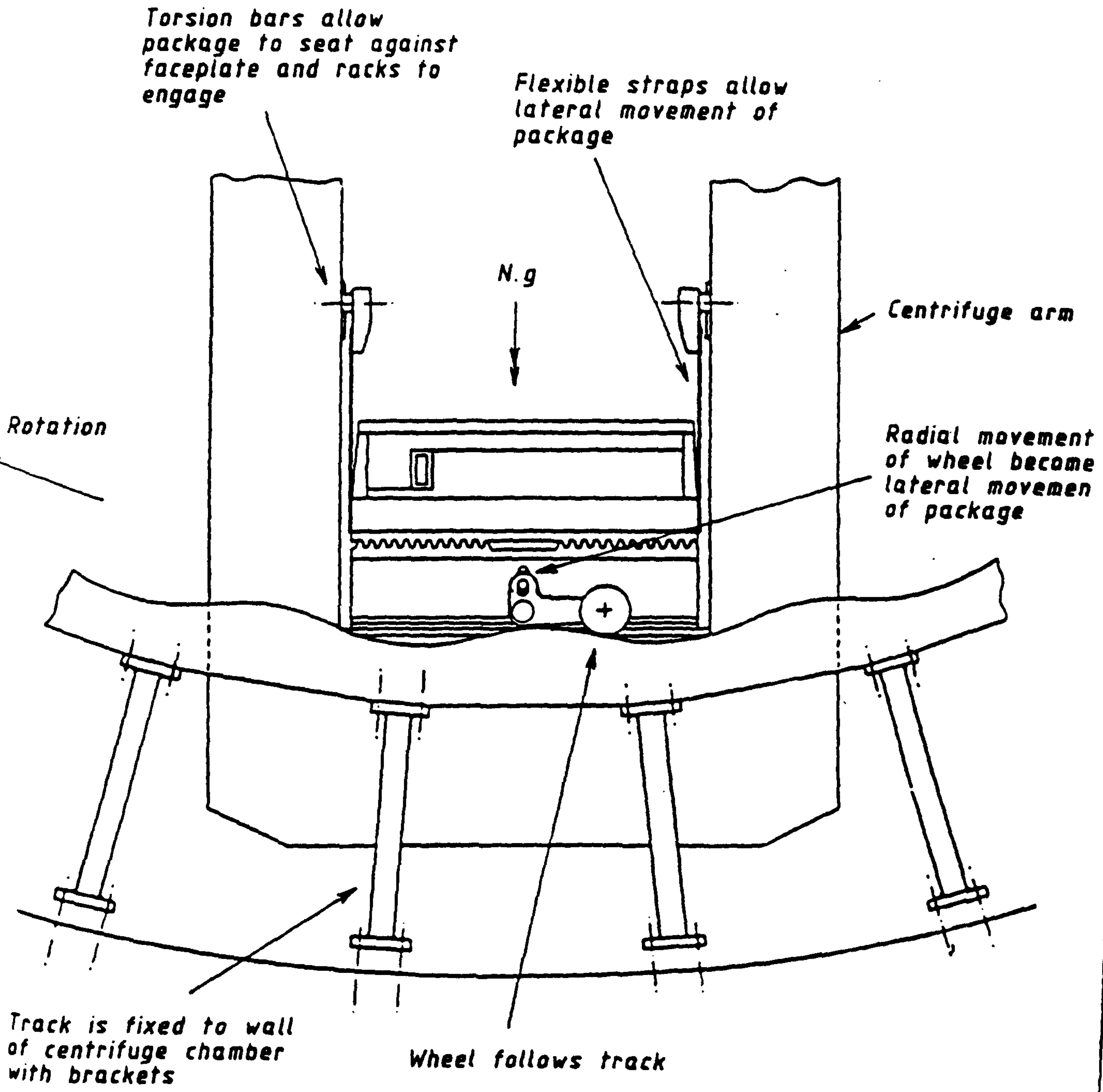
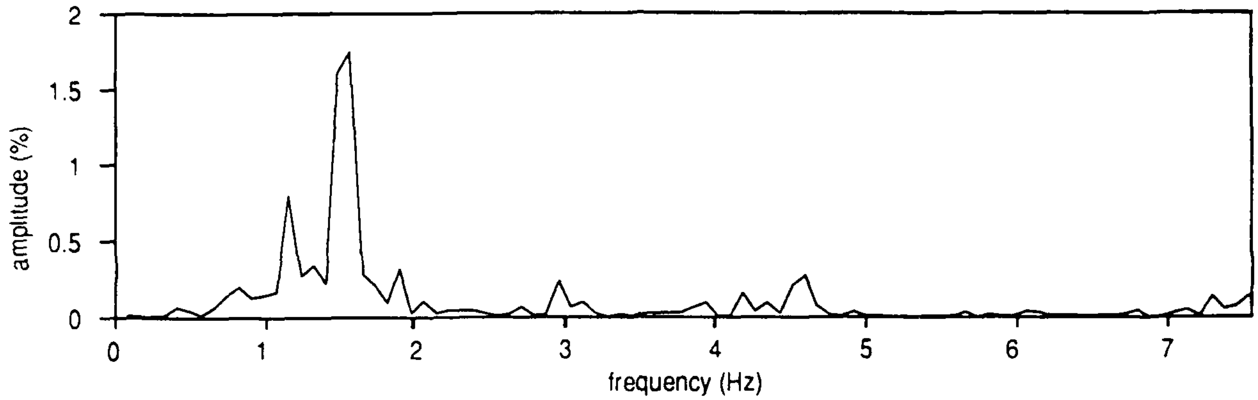
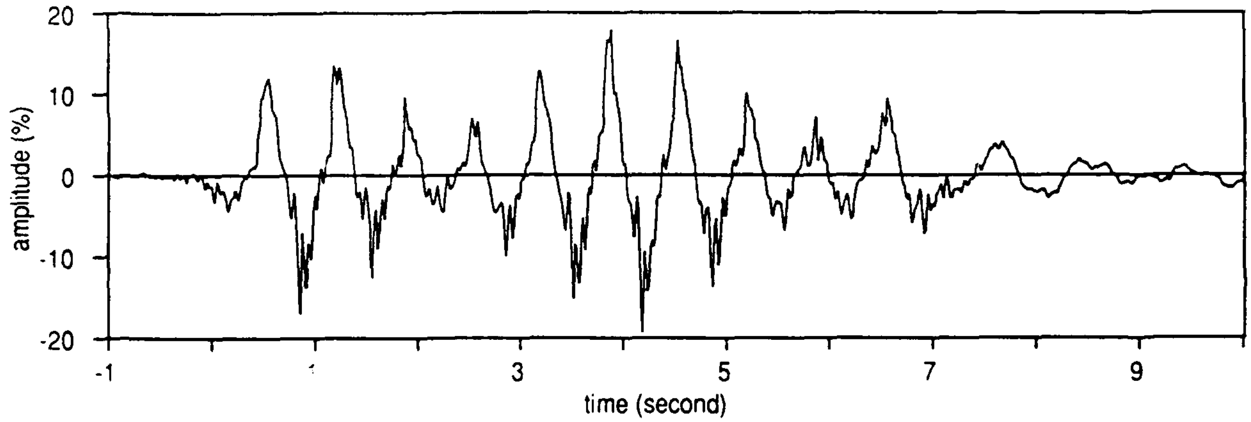


Fig. B4 Cut-away view of the Bumpy Road Earthquake Actuator



Fourier amplitude spectrum of earthquake input



time recording of earthquake input

Fig. B5 Typical earthquake input from the Bumpy Road Actuator

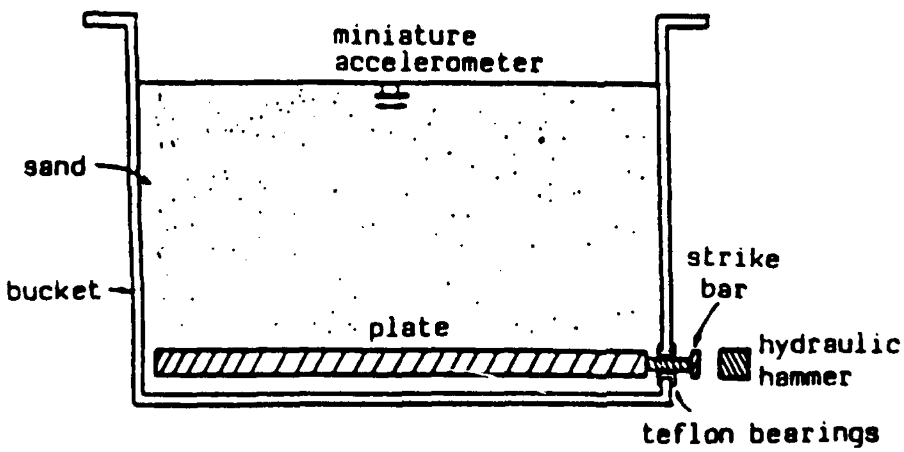


Fig. B6 The hammer plate shaker at Princeton, Coe et al.

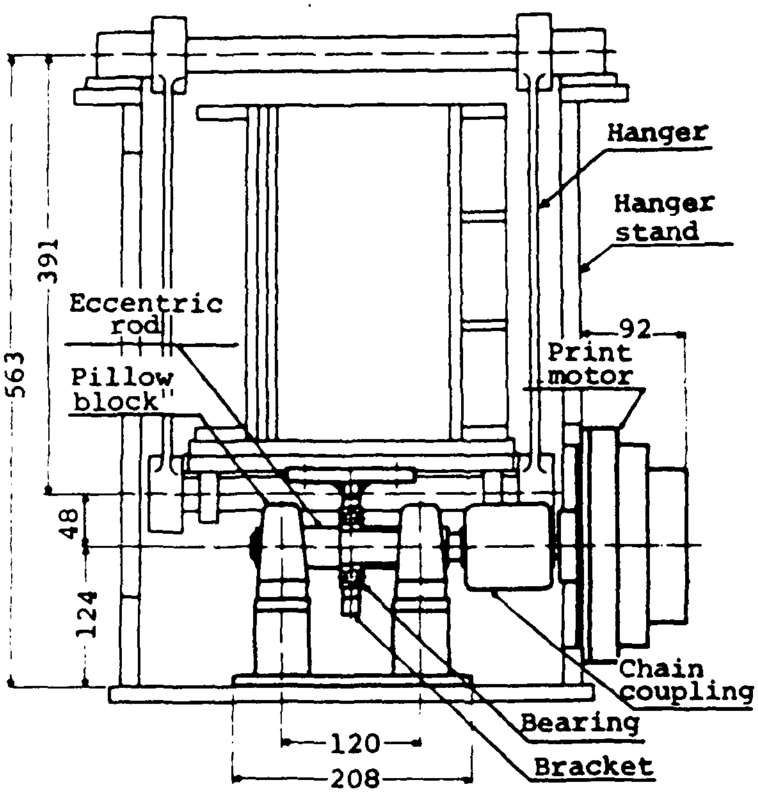


Fig. B7 The eccentric cam shaker at TIT, Kimura et al.

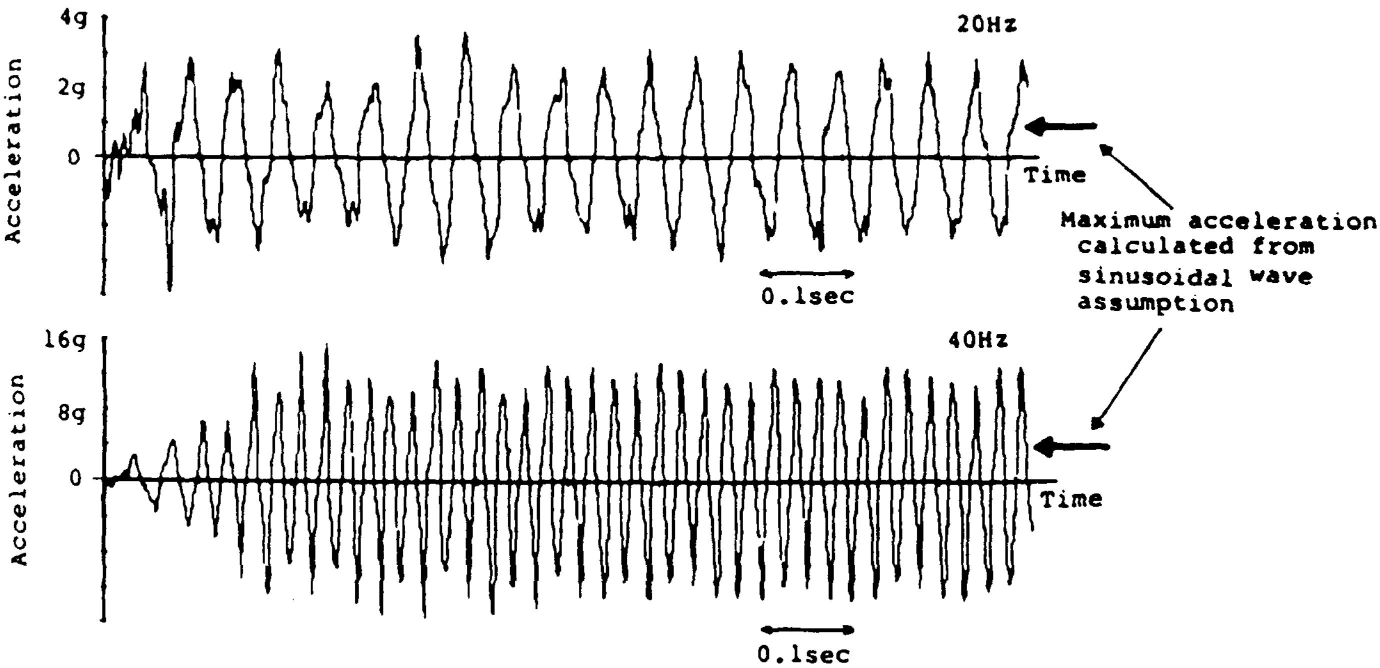


Fig. B8 Typical input motion of the eccentric cam shaker at TIT, Kimura et al.

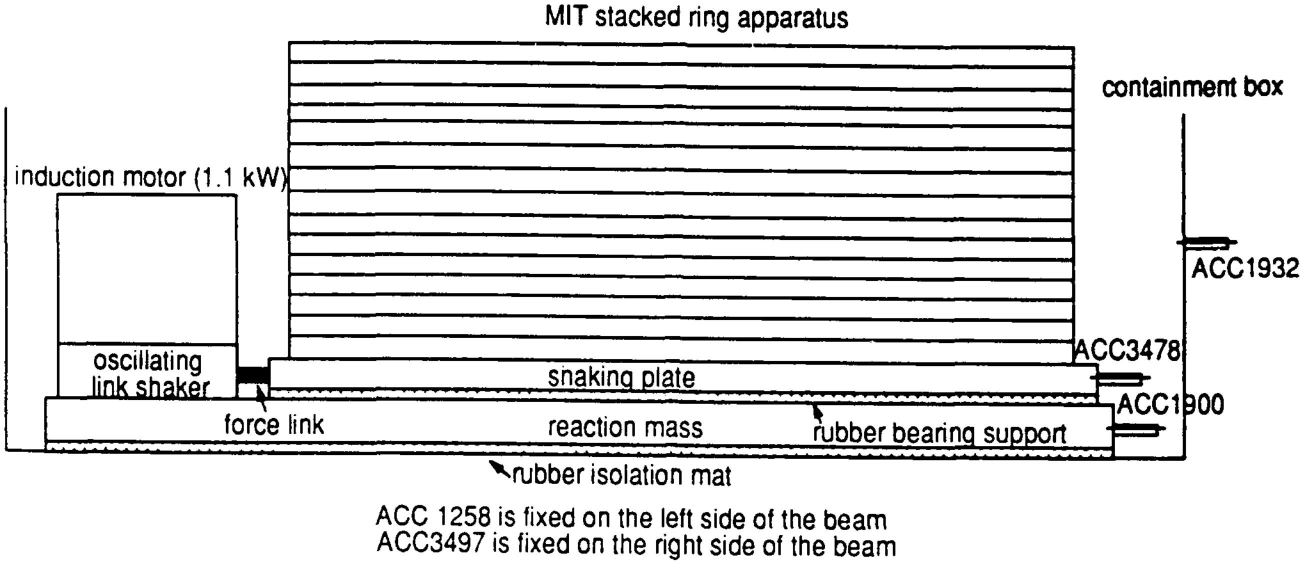


Fig. B9 The oscillating link shaker at Cambridge

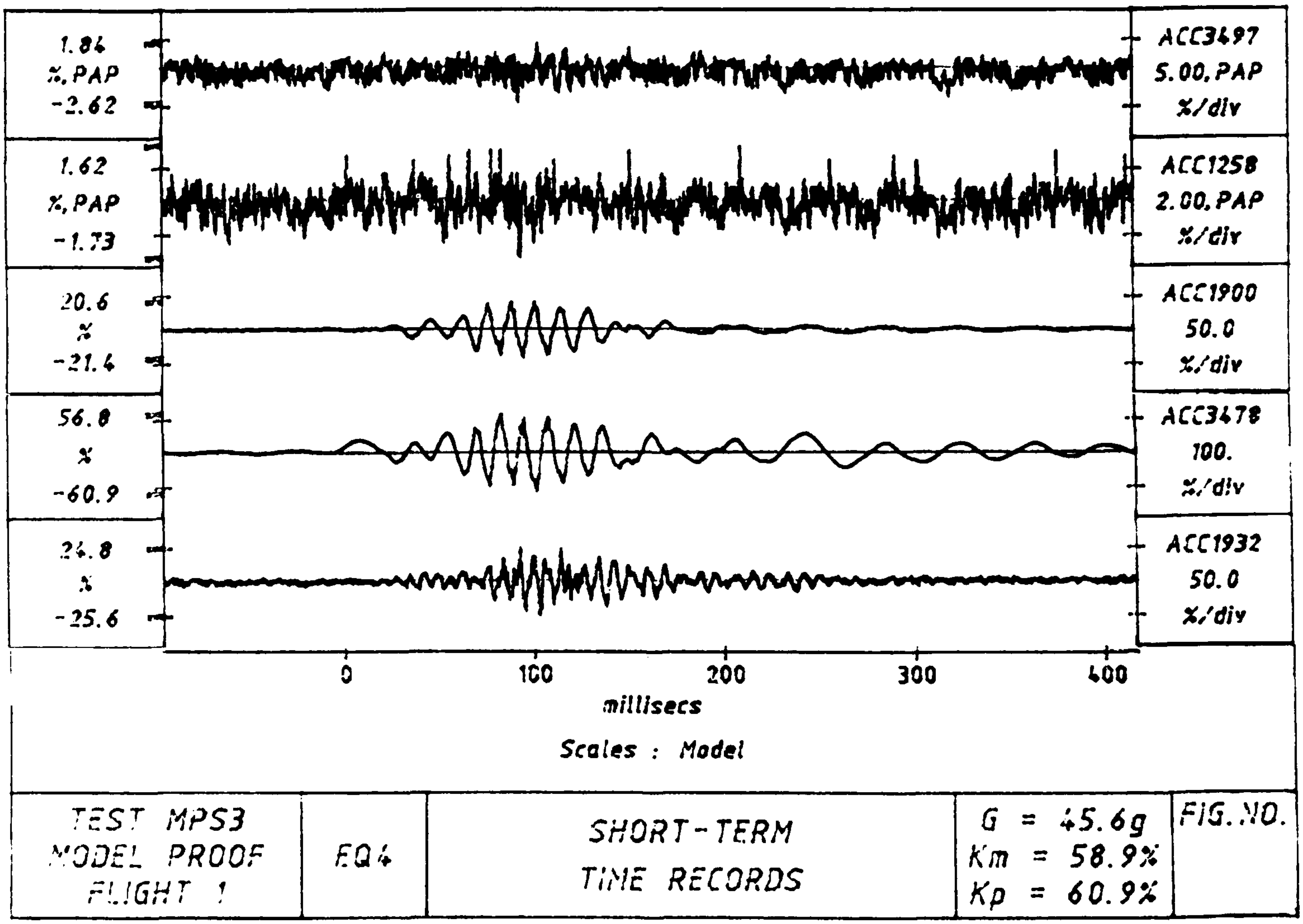


Fig. B10 Recording of some transducers in the proof test of the oscillating link

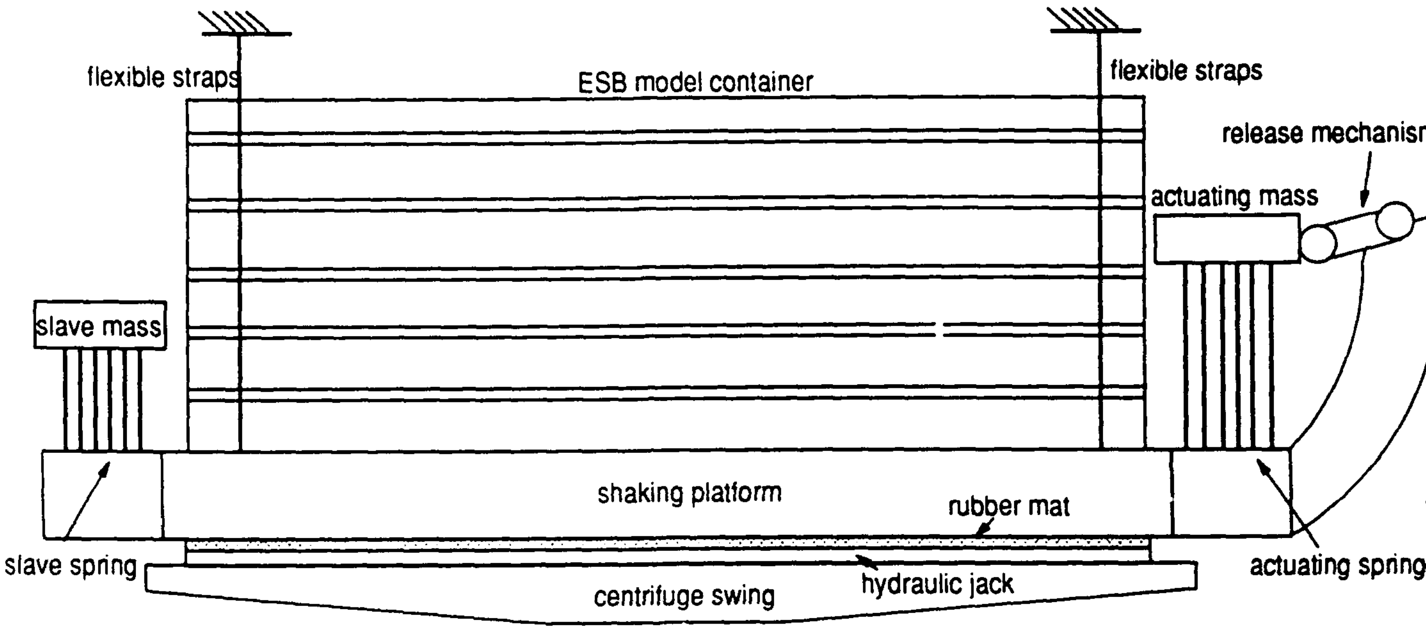


Fig. B11 The advanced spring-actuated shaker at Cambridge

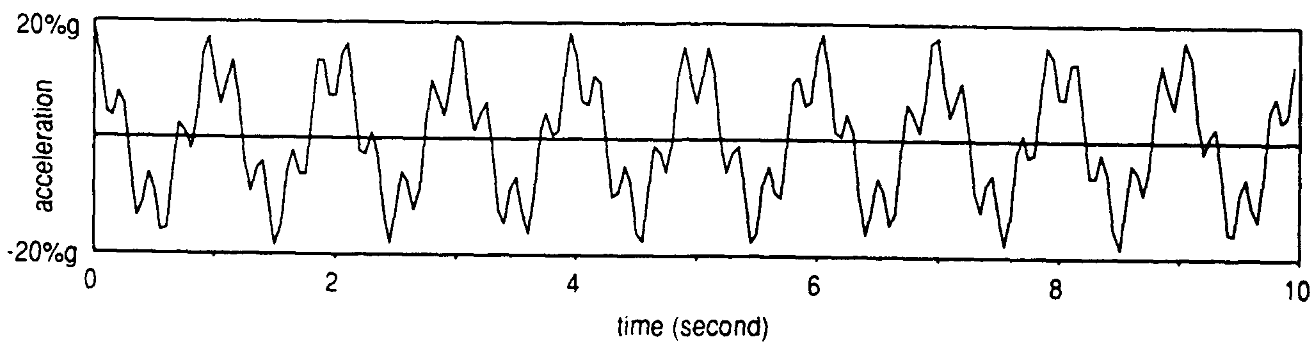


Fig. B12 Theoretical input motion from the advanced spring-actuated shaker

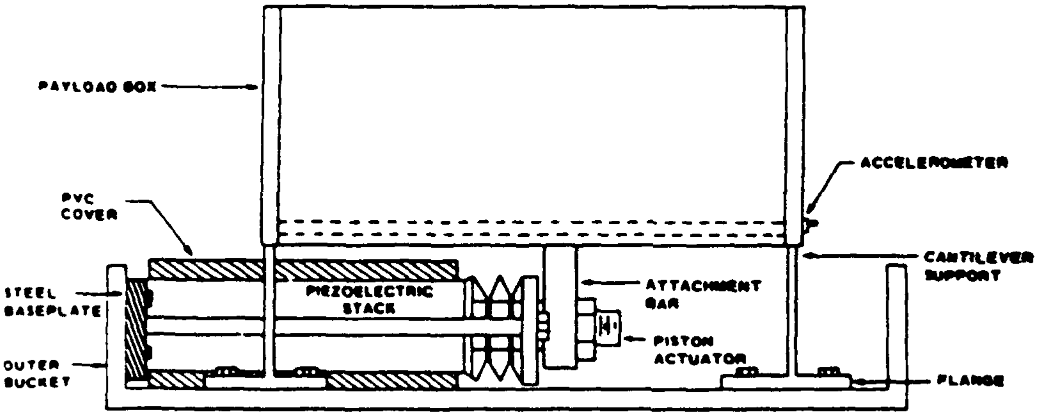


Fig. B13 The piezoelectric shaker at UC Davis, Arulanandan et al.

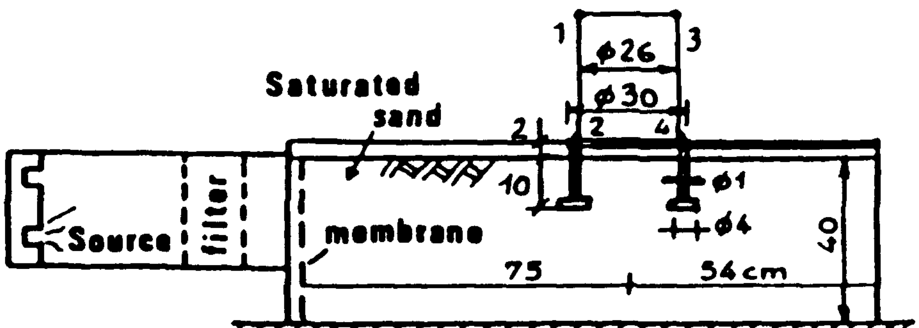


Fig. B14 The explosive shaker at CESTA, Zelikson et al.

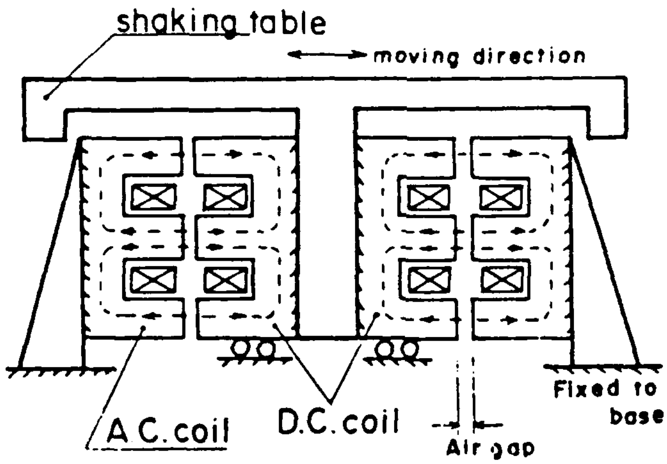


Fig. B15 The electromagnetic shaker at Chuo University, Fujii

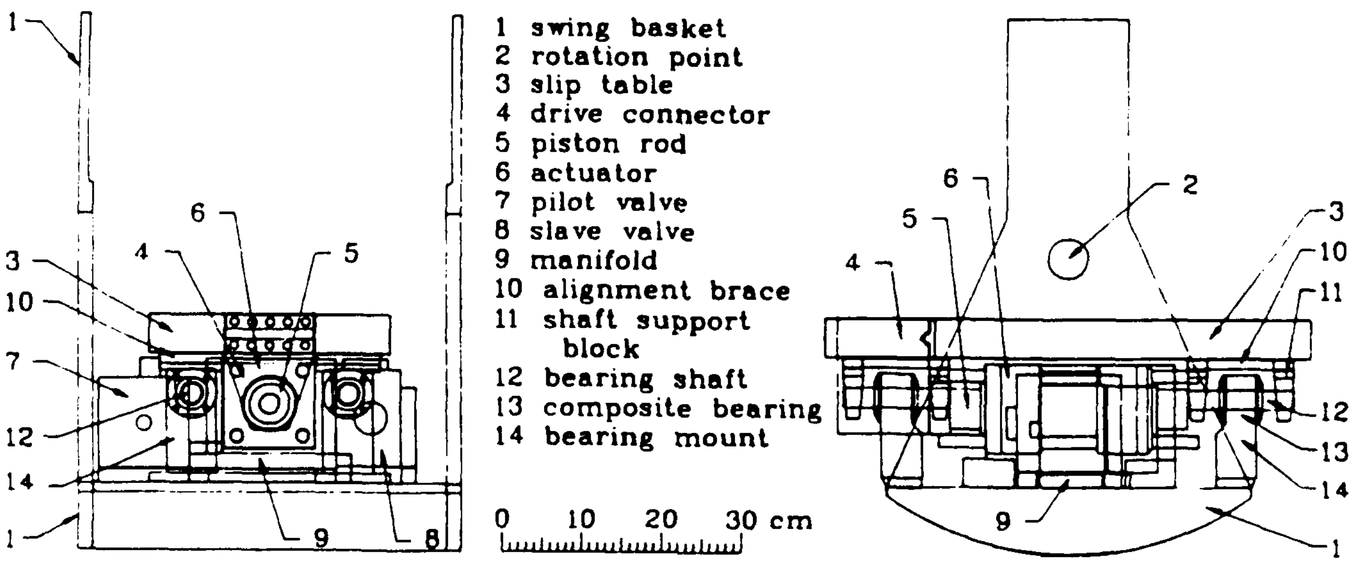


Fig. B16 The electro-hydraulic shaker at Colorado University, Ketcham et al.

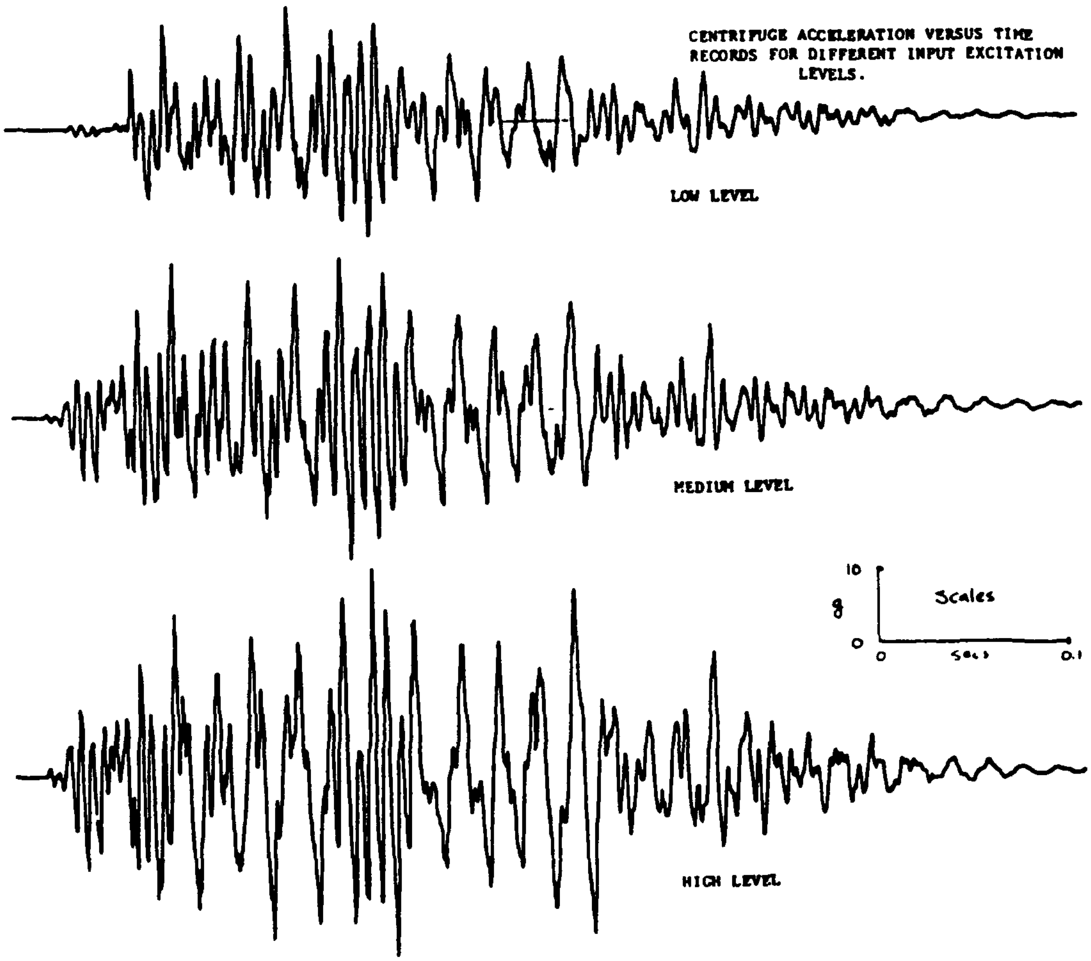
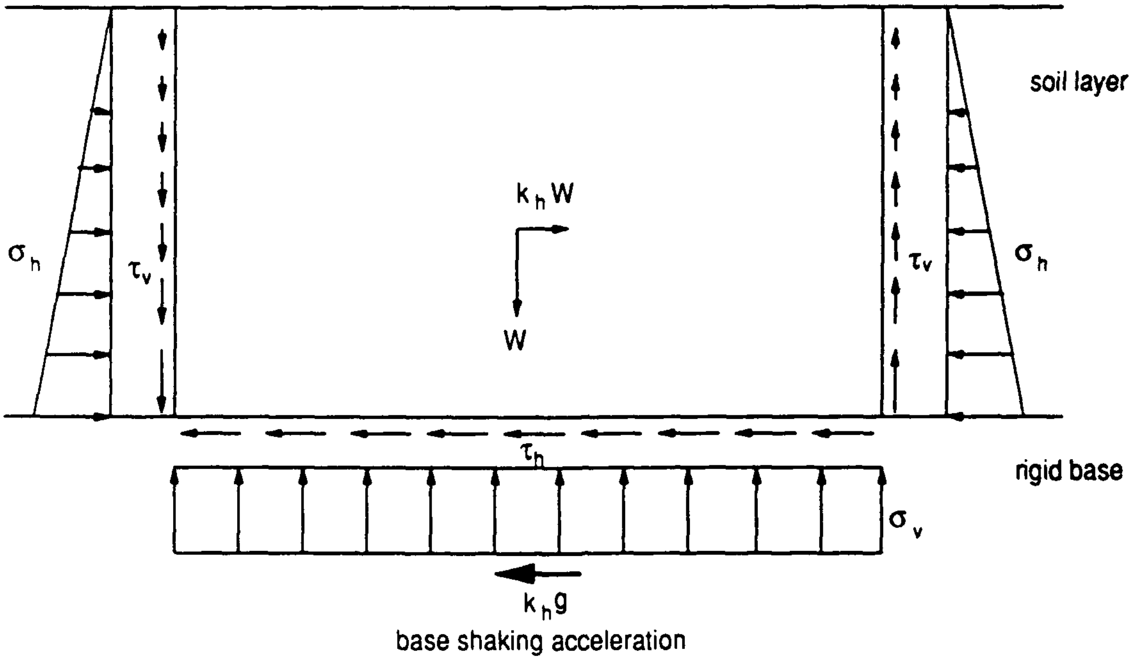
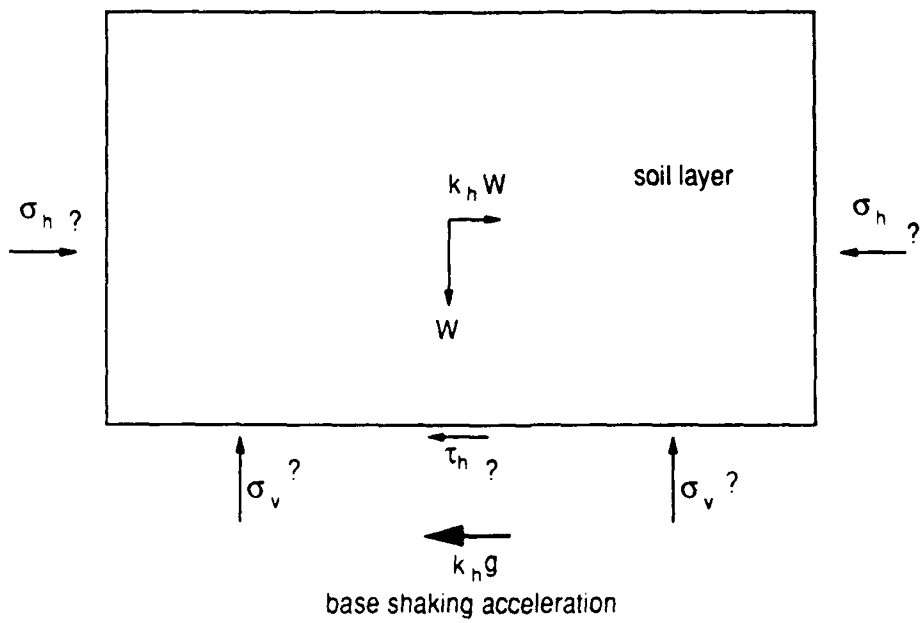


Fig. B17 Typical input motion generated by the hydraulic shaker at Caltech



a) distribution of stresses in an infinite soil layer



b) distribution of stresses in model with smooth rigid end walls

Fig. B18 Distortion in stress field due to smooth end walls

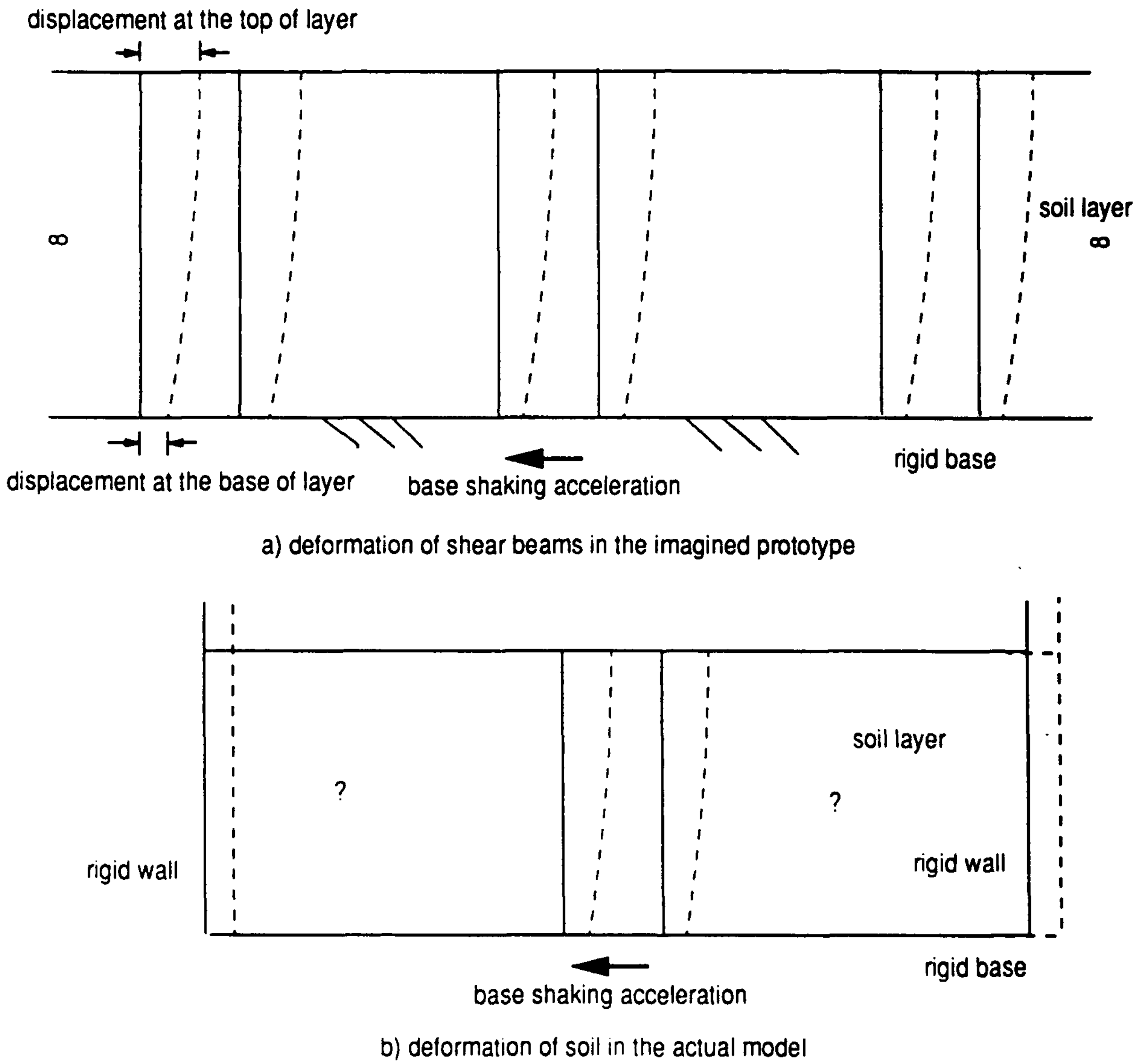


Fig. B19 Deformation of soil in a model container with rigid end walls

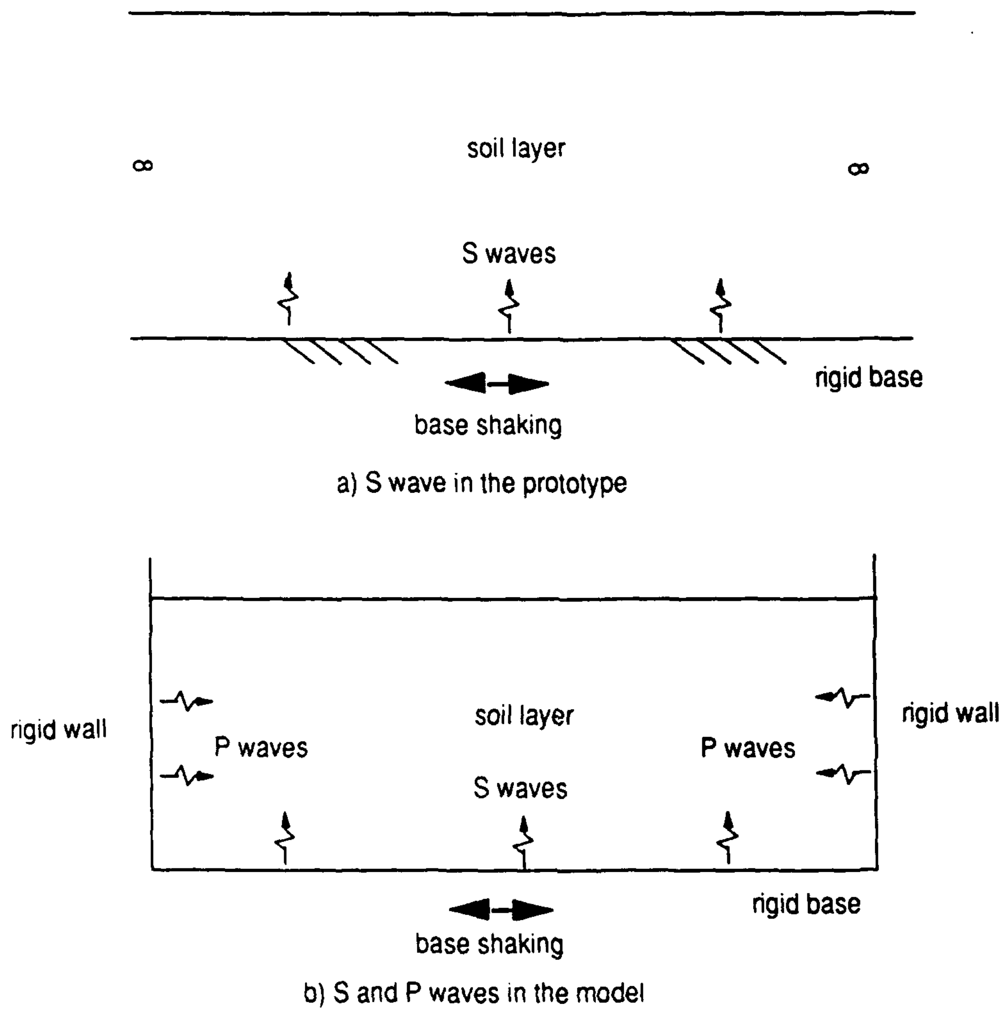


Fig. B20 Seismic waves in model and prototype

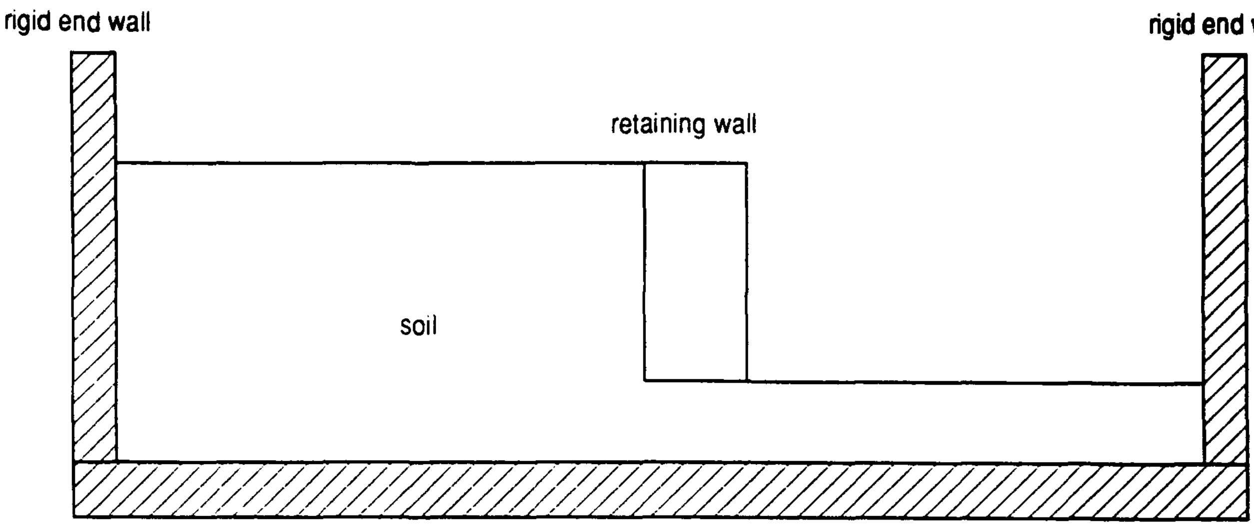


Fig. B21 Rigid end wall boundary

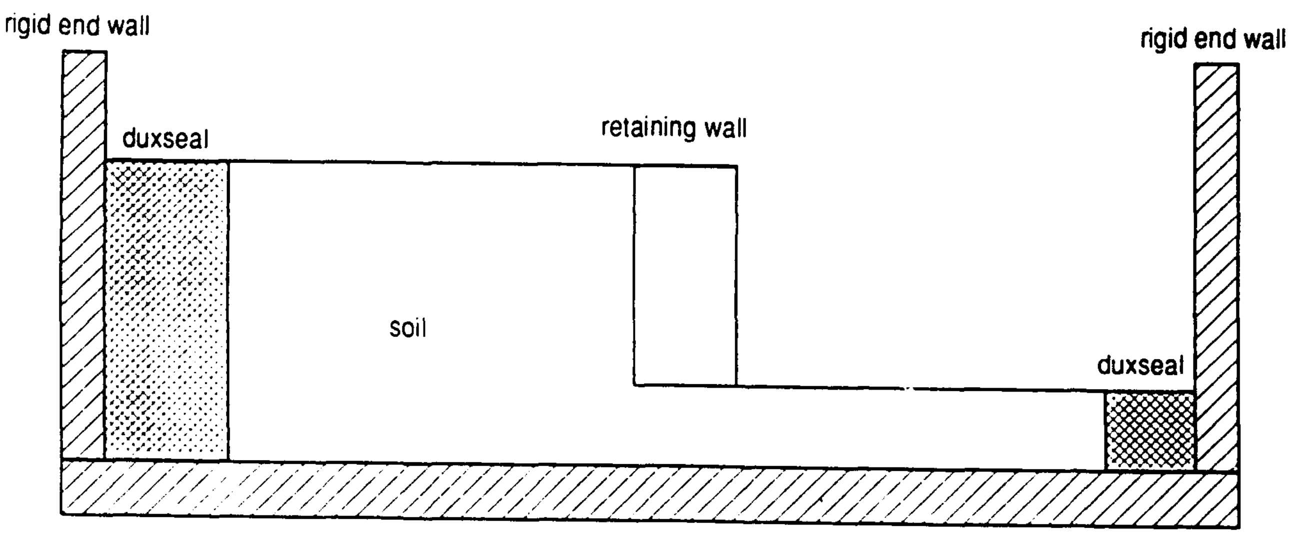


Fig. B22 Soft absorbing boundary made of Duxseal

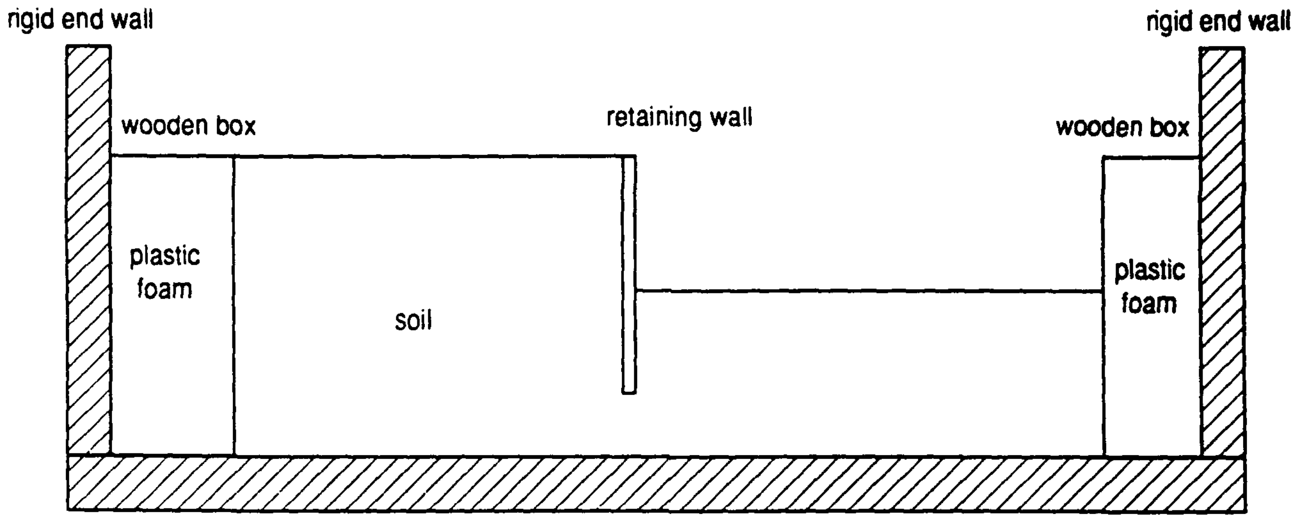


Fig. B23 Rigid absorbing boundary, Zeng

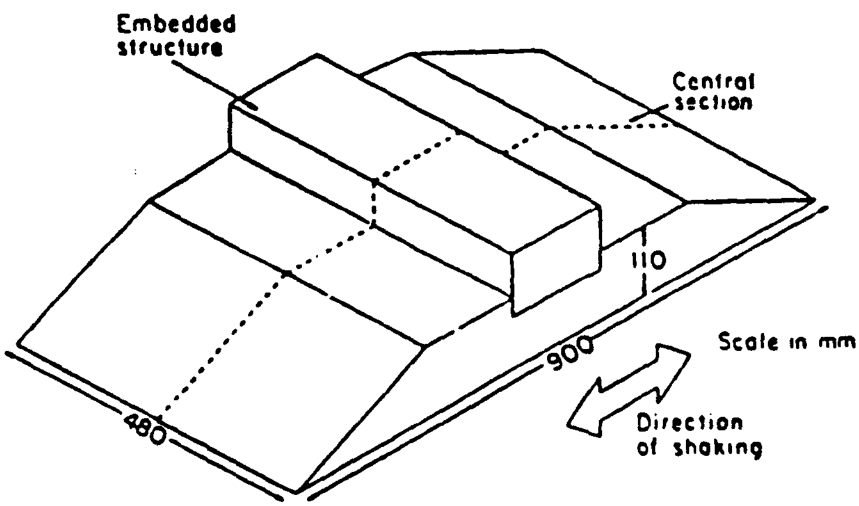


Fig. B24 Free slope boundary, Finn

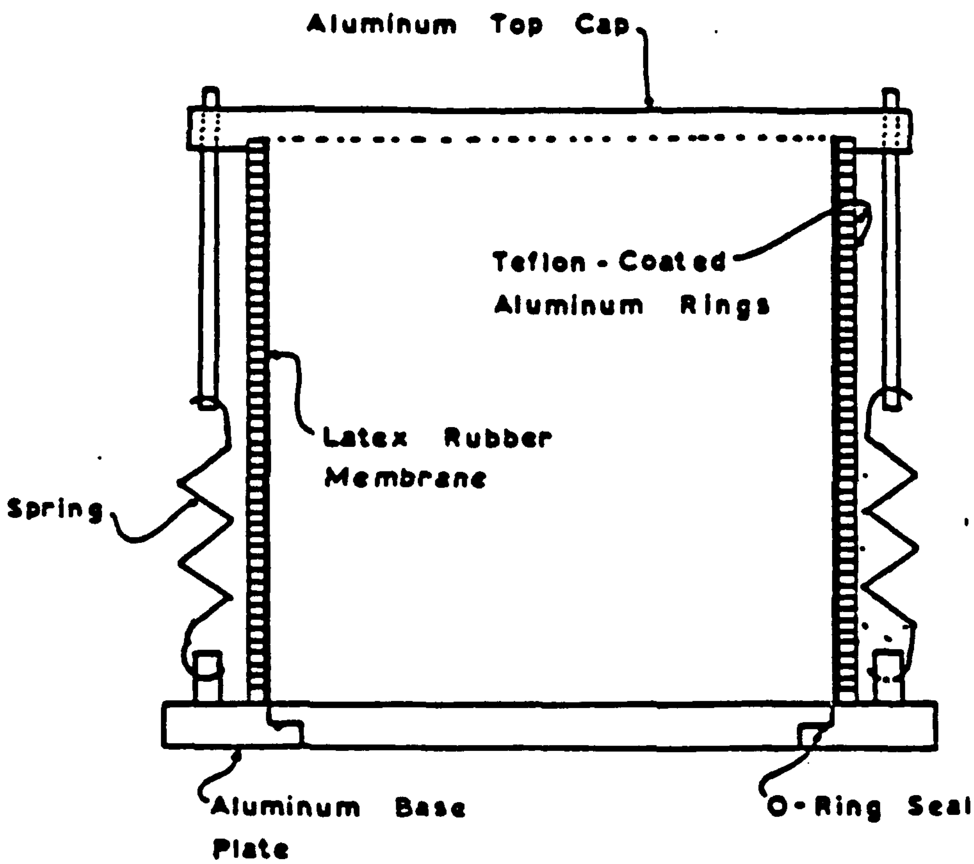


Fig. B25 The stacked ring device at MIT, Whitman et al.

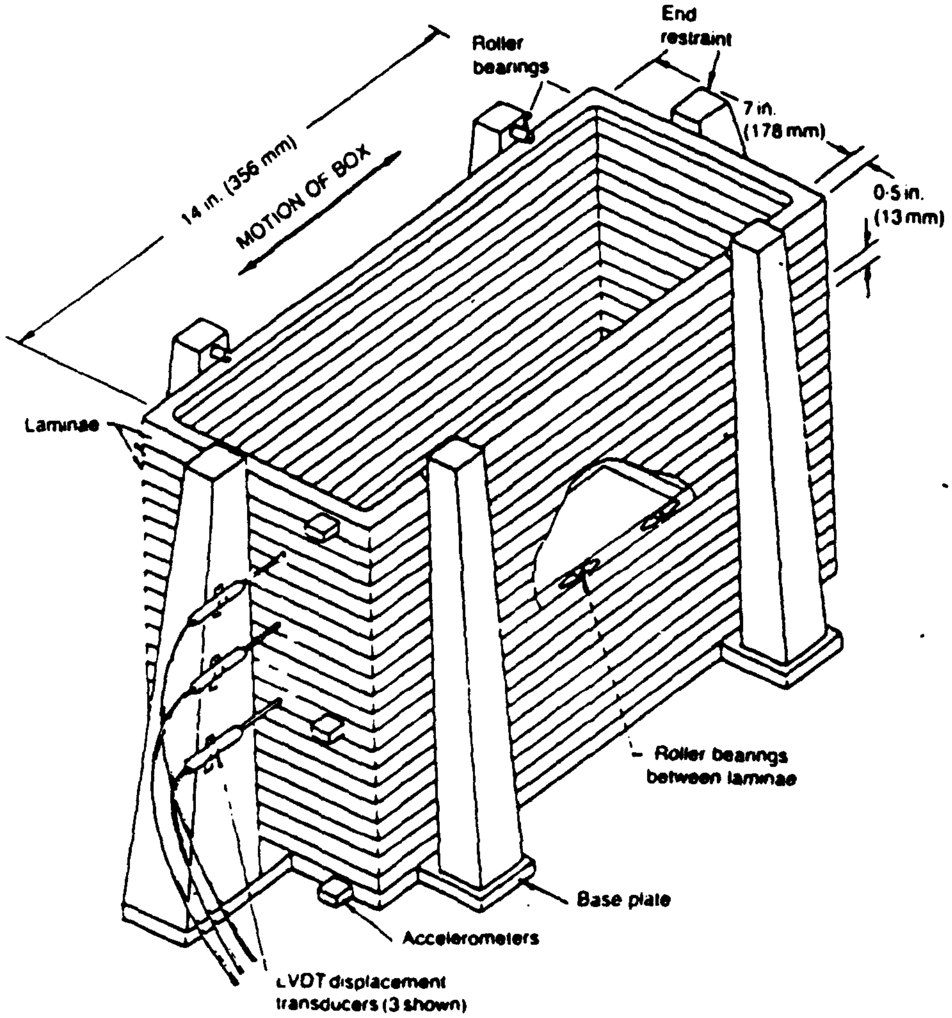


Fig. B26 A sketch of the laminar box at Caltech, Hushmand et al.

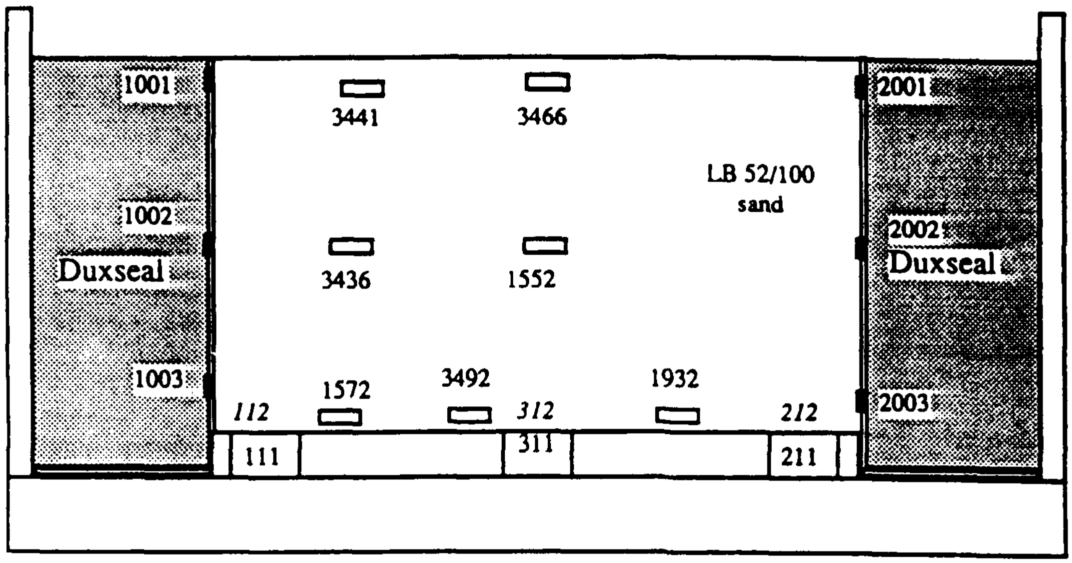


Fig. B27 An absorbing and frictional boundary, Madabhushi et al.

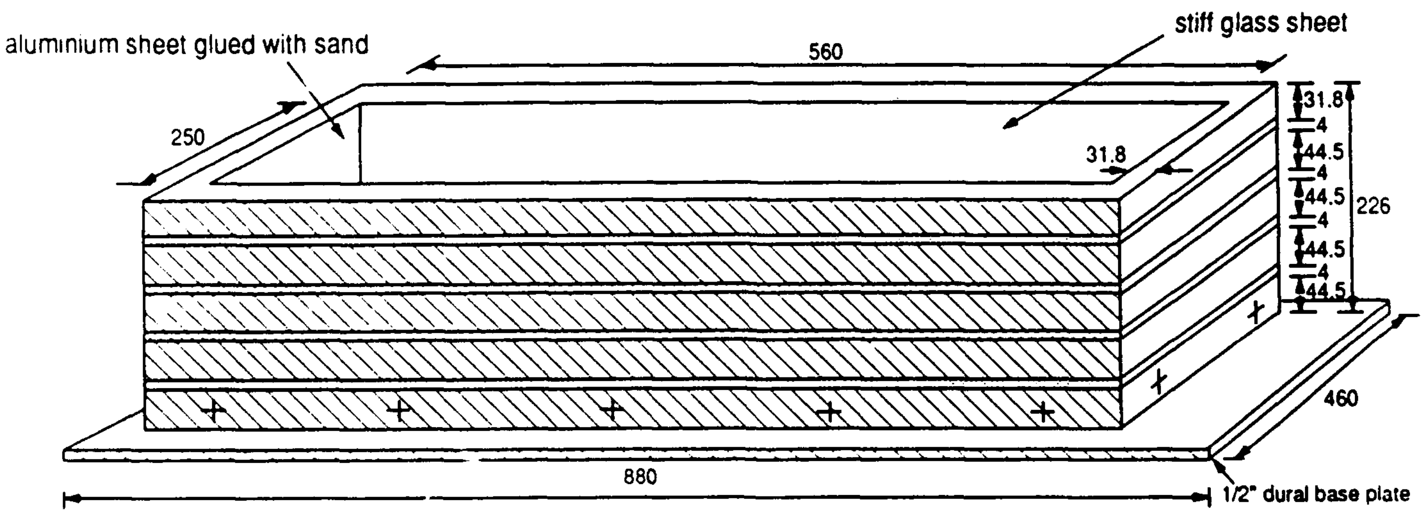


Fig. B28 The ESB container, Schofield et al. (units in mm)

APPENDIX C

DESIGN OPTIONS FOR CONTROL OF THE THERMAL ENVIRONMENT IN A CENTRIFUGE MODEL TEST PACKAGE

Summary

There are a range of options for the implementation of full temperature control over a centrifuge model's boundaries, both while in preparation and in flight. This Appendix to ANS&A's Report 25-02-R-004 describes methods of adding and removing heat from a model and the various sources of heating and cooling that could be used. The design of three separate packages is outlined, covering the requirements of three distinct types of model tests, the most complex of which involves the control of the model base temperature and the air temperature above the model surface while maintaining the side walls insulated. The need to control the air humidity in certain models so that surface evaporation can be controlled is also identified. In order to investigate some of the temperature control options outlined in this report, a package was developed at Cambridge that incorporated some of the suggested cooling/heating systems. A description of the design and operation of this apparatus is also included.

APPENDIX C: CONTENTS

C1.0 Design Considerations

C1.1 The need for environmental control of a centrifuge model

The centrifuge testing of engineering models continually advances in sophistication and with increasing interest in modelling frozen soil, unsaturated soil, pollution migration, heat transfer, hydraulics, sea and freshwater ice, which are all temperature and humidity sensitive, a method of accurately controlling these parameters is desirable at all stages from lab floor construction to in flight testing of the model. In order to consider in detail the range of temperatures, heat transfer rates, and humidities that may be required from a package, it is necessary to consider the scope of tests for which temperature and humidity/ evaporation control would be desirable. The following table lists a selection of situations where temperature and humidity control are an important area of interest.

Geotechnical engineering	Cold regions engineering	Environmental & Hydraulic engineering
ageing of clay	sea ice growth/pressure ridge	pollution migration
accelerated soil creep	natural soil features	conduction and convection in soil
accelerated geotextile creep	frost heave & thaw settlement	electro-osmosis
thermal drilling	pile jacking	clay damage due to heating
unsaturated soils	freeze/thaw effects, eg. landslides	wave action
	creep of frozen soil	

From an assessment of each individual test, a general specification for the temperature range, power requirements and air conditioning required of an environmental package can be stated. Naturally, all soil tests will be affected by temperature and humidity: in particular, environmental control will benefit standard clay model tests which may suffer from pore pressure transients when a model is transferred from the laboratory to the thermal environment of the centrifuge enclosure. Such models may also suffer from an excessive drying out due to evaporation processes in circumstances where the clay test is performed in an open tub without the presence of surface water. Centrifuges sited in warm parts of the world may also suffer from extreme temperatures in the centrifuge pit which may have adverse effects on the models. In the case of the U.S.A.E. Waterways Experimental Station, their powerful centrifuge will indeed have a major effect on their centrifuge pit temperature. The environmental control of a model sample therefore has two functions: firstly to shield the model from extreme variations of pit temperature, and secondly active control of boundary conditions within the interior of a model test package.

This need for temperature and humidity control of geotechnical models both on the lab floor and in a centrifuge test can be broken down into two distinct modelling types: models requiring large temperature transients and phase change with large magnitudes of heat extraction or input, and those requiring fairly steady state conditions with heat input/output necessary to overcome insulation losses. Precise control of the boundary conditions is desirable, ensuring uniform temperature distributions and depths of frozen/thawed soil.

C1.2 Envisaged Heating and Cooling Requirements

C1.2.1 Temperature Ranges

In general, the model temperature requirements for a wide selection of tests will range between -70°C to +95°C. The low temperature being required for the study of extreme chilling effects on frozen soil and ice, while the high temperature may possibly be required in the study of soil/geotextile creep and the ageing of clay. However a smaller range still of very general use would be between -40°C and +70°C, with only a few special applications requiring the larger range.

C1.2.2 Power Requirements

The tests listed in the above table can be divided into two distinct classes, each requiring correspondingly different magnitudes of heat extraction/input.

(i) Small heat input/output requirements. These include tests that require only:

- maintenance of a constant temperature in the model (overcoming insulation losses),
- maintenance of a small geothermal gradient,
- or extraction of small quantities of heat generated by a structure within the model.

These processes will typically require of the order of ≈ 30W of cooling/heating per square metre of all round surface area of a well insulated model box (see Appendices F and J of this Report).

(ii) Large heat input/output requirements.

Such tests may involve:

- full freeze/thaw modelling preferably occurring over a simulated `centrifuge year' (this involves extraction and input of large amounts of cold/heat which is absorbed by the large latent heat capacity of the soil water),

- freezing of sea or fresh water to form ice,

- extraction of large quantities of heat generated within the model itself (chemical and electrical effects).

It can be seen from Appendix F that for example, to correctly simulate an annual freeze thaw cycle of soil with the surface temperature varying by plus/minus 10°C about freezing, then a peak of over 3.5 kW of heating or cooling capacity per square metre of soil surface at a scale of 1:100 is required, over and above that to overcome insulation losses. This heat flux requirement per square metre, however, scales directly with the model scale and so reduces at lower acceleration levels.

C1.2.3 Boundary Conditions

Almost all applications will be satisfied by the temperature control of the model base and of the air above the model. The most straightforward and useful side boundary conditions are adiabatic and can be easily achieved passively using insulation. The top or bottom conditions can be maintained as isothermal or as a controllable power input/extraction boundaries using a combination of cooling plates and heating elements, with sensors and feedback control. It is essential that uniformity of heat transfer (when desired) can be achieved so that uniform conditions or depth of freezing or thawing can be maintained and relied upon. Implementation of the cooling or heating of the sides is possible but would increase the equipment complexity by a significant amount for little overall gain. However control of the power input/output rates means that in this case, active maintenance of an adiabatic boundary could be achieved.

C1.2.4 Air Conditioning

In experiments involving fine grained, or partially saturated soils, there is a need to seal the package from the outside world in order to prevent excessive evaporation. However, tests that envisage evaporation (or condensation) and control of dew point as an essential part of the experiment will also require some form of air moisture extraction/input system. This is, however, of a lower priority than temperature control and is probably best implemented specifically for individual tests. It should however be considered in the initial design phases in order that later implementation is simplified. A further possibility that may occur during the progress of an an electro-osmosis experiment involving pollutants, is the generation of gases eg. chlorine or hydrogen which may need venting, and thus require a circulation of air.

C2.0 Methods for adding/removing heat from the model

Section C2 considers methods for transferring heat energy from a cold/heat source to or from the model itself. The discussion is independent of the actual source of cooling or heating chosen, and focuses on the heat transfer to the model surface and the model base. This is most relevant to a system requiring large heat input/extraction. Systems requiring a constant temperature are more straightforward and are considered in more detail in Section C7.

C2.1 Transfer of energy to the free surface of a model

The transference of heat energy to and from a model free surface is complicated by the necessity to maintain a zero stress condition at zero depth and to permit unrestrained surface movement. An air gap above the model surface is thus necessary. Heat may thus be transferred to the model surface either directly or indirectly as follows.

Direct heat transfer could involve the use of a cold air stream or `wind' blowing across the model to provide a rapid method of cooling. However it has several associated problems as follows :

- as the cold air passes over the surface it warms up, causing uneven cooling of the

model surface. This will especially occur in circumstances where a high heat transfer rate is needed.

- regardless of whether the air circulated is in an open or closed loop, moisture may be transferred from the model surface and deposited elsewhere in the cooling system.

- a cold air generator is required.

- the velocity of the required air stream may be such as to damage the model.

Having said this, judicious arrangement of the air flow pattern over the model surface may reduce the unevenness of the heat transfer. Several options can be considered:

- air can be blown laterally across the model, perhaps using a graded system of baffles to create turbulence, and to spread the air flow (and so the heat transfer) evenly across the model;

- air may be injected downwards through a central hole above the model and vented through holes at the sides or vice versa;

- air can be injected at several locations and then vented at intermediate positions.

The choice will be determined by what gives the best heat transfer. It may be sensible to circulate the air through the lid itself after it has passed over the model so as to extract the maximum possible energy. Appendix G details the average heat transfer rates to be expected from a cold 'wind'. For example, a flow rate of 50 litres/s/m width at a temperature of -40°C can transfer up to 1.5 kW/m^2 to a model surface at temperature 0°C, over relatively short lengths.

An alternative system for use in situations where extremely high cooling rates are required could involve the use of evaporative cooling. This may involve, for example, the spraying of liquid nitrogen droplets onto the model surface which would then evaporate. A system of this nature, however, is likely to be very difficult to engineer and to control.

Indirect heat transfer involves the mounting of a heat exchanger plate a small distance above the model surface and relies on conduction, convection and radiative heat transfer through the air to transfer heat between it and the model. If a uniform plate temperature is maintained, then this has the advantage of giving uniform heat transfer across the entire model surface and additionally of maintaining an enclosed air volume above the model surface, eliminating any moisture loss/gain problem. Its main disadvantage is in the complexity of the required lid which may limit the addition of extra instrumentation. The system, however, will be independent of the cooling source chosen.

Appendix G details the computation of heat transfer between a plate and the surface of a model. For example, a cooling plate maintained at -50°C will transfer approximately 750 W/m^2 to a model surface at 0°C at a centrifuge acceleration of 50g, and the heat transfer will be virtually independent of the plate/model surface separation. The disadvantage of this system is its lower heat transfer capacity at low model accelerations, due to reduced convection. However, in simulating any given prototype situation, the

heat flux to be modelled will scale directly as the model scale factor and thus at lower accelerations, a lower heat flux will be required which will tend to counteract the reduction in heat flux capability (see Appendix G).

In circumstances where the model needs to be warmed up, the transfer of heat from a now warm plate to a cooler model surface will clearly involve minimal convection and so the same rates must be achieved with a higher plate temperature to maximise radiative transfer. Fortunately, the generation of heat is much more straightforward than of cold. If the maintenance of an air gap above the model surface was not deemed essential, then filling it with eg. lightweight shredded aluminium foil would markedly improve the heat transfer capabilities. Alternatively a more conductive/convective gas than air could be used in the chamber such as Helium. This however would require a good sealing of the air gap between the model surface and the plate above.

A flexible design may permit both modes of heat transfer to be used and switched between in flight using valves.

C2.2 Transfer of energy to the model base

Since an air gap is not necessary, transfer of heat to the model base is clearly much less of a problem than to the surface and direct conduction is possible. Consideration, however, must be made of the supply of water to the model base via a drain. The design of base must therefore take account of the following considerations:

- it must be strong enough to take weight of model or package.
- it must provide drainage holes for model, if it is an integral part of the package, such that the pressure boundary condition at the base can be controlled.
- in order to provide easy access to the model after a test, it is useful to be able to detach the base from the model box sides so that the model can be easily sectioned.

C2.3 Design of sides

For models held at constant temperature or at a constant temperature gradient the model box can be constructed of dural or steel. Insulation can then be attached to the outside of the package or be provided by a separately insulated swing. In contrast, for models undergoing temperature transients it is necessary that the box walls be insulated, and so constructed from either high density plastic or plywood. This must be either thick enough to take all the envisaged stresses in centrifuge flight, or be supported by additional packaging and an external strong box so that the lateral stiffness of the insulated sheets will not affect model stresses. The thickness of the insulation required will be dependent on the ratio of model conductivity to insulation conductivity. During the modelling of freezing processes, account must also be taken of the potential for large lateral stresses being induced by the expansion of the water during its transition to ice.

C3.0 Sources of coolth/heat

C3.1 Options for source of coolth

This section considers the several choices that can be made for the cooling system. Each will be considered in turn as follows together with its advantages and disadvantages.

Passing of liquid refrigerant down to the package via the slip rings at up to -55°C, possible secondary refrigerants are alcohol, glycol, or silicon fluid, or liquid nitrogen.

- advantages: All cooling done external to arm (requires refrigeration plant or dewar of LN_2). Large power capacity.

- disadvantages: Inevitable heat loss on passing down the slip ring to arm. High pressure in circulating fluid at package - safety hazard if leaks develop. High pressure fittings required. May require fitting of new slip rings. Safety problem with very cold refrigerant leaks which could cause damage to the centrifuge itself.

On arm refrigeration unit, circulating liquid secondary refrigerant (as above) to package.

- advantages: Fairly large power capacity. No slip ring changes.

- disadvantages: High head of fluid at package. Safety hazard if leaks develop. High pressure fittings required. Safety hazard if refrigeration plant fails. Specialised refrigeration plant design required at high g-levels. Largish unit required. Balancing necessary.

Expansion of high pressure air/nitrogen through an expansion turbine to achieve cooling.

- advantages: Uses existing slip rings. Small unit. Circulation of air does not give rise to high pressures at package. Reasonable power delivery. Direct source of cold air if direct cooling of model surface chosen.

- disadvantages: High flow rates of air required to achieve necessary cooling. Turbine may operate at high speeds, of the order of 10000 rpm . Even in a position near the centrifuge axis there is a possibility of damage/unbalancing this precision device. Safety: if turbine shatters - strong enclosure required to contain it. If use air as gas then possibility of fire if unbalanced turbine generates high friction temperatures. Gas used needs to be dry to prevent icing up - either use dehumidifier in conjunction with compressor or use bottled nitrogen (cheaper short term option). Possibility of condensation erosion.

Expansion of high pressure air/nitrogen through a vortex tube to achieve cooling (see Appendix H).

- advantages: Uses existing slip rings. Small unit. Circulation of air does not give

rise to high pressures. Moderate power delivery. Useful for direct cooling application. Also generates warm air stream - useful for heating applications. No moving parts. Safe. Cold is generated in the package - no loss of heat in slip rings.

- disadvantages: High flow rates of air required to achieve necessary cooling (air must be lubricated to pass through slip ring and then de-oiled for vortex tube). Not as efficient as a turbine perhaps 1/2 cold gas throughput. Gas used needs to be dry to prevent icing up - either use dehumidifier in conjunction with compressor or use bottled nitrogen (cheaper short term option).

Preload refrigerant on arm - e.g. dry ice or liquid nitrogen.

- advantages: No slip ring modifications. Low temperature available.

- disadvantages: Not a continuous supply. Safety considerations for the containment of the liquid/solid.

Cooling using solid state Peltier effect heat pumps (see Appendix I).

- advantages: Precise electronic temperature control of localised areas. Can typically achieve up to a 60°C temperature differential. No moving parts. Small device. Can be used as a heater in reverse mode.

- disadvantages: Generation of a high temperature differential results in a lower power transmission. Operation of device generates additional Joule heating which needs to be dissipated, this becomes very large for a high heat pumping rate, and requires extra cooling. Careful mounting in the centrifuge acceleration field required to eliminate large stresses on this relatively fragile device. Specialised power supply requirements - low voltage, high current.

C3.2 Options for source of heat

Again, there are several choices that can be made for the heating system. These can be listed as follows.

Expansion of high pressure air/nitrogen through a vortex tube to achieve heating, (see Appendix H).

- advantages: As for previous consideration. Also generates cold air stream - useful for cooling applications.

- disadvantages: As for previous consideration.

Electrical heating of a pumped air stream.

- advantages: With feedback, can give good control of temperature. Can be used in conjunction with a cold air stream providing a wide range of

temperatures.

- disadvantages: Requires air supply through slip ring. Only suitable for direct air heating.

Electrical heating of a plate.

- advantages: With feedback, can give good localised control of temperature. Robust.

- disadvantages: Only suitable for indirect surface heating.

Heating using solid state Peltier effect heat pumps (see Appendix I).

- advantages: Precise electronic temperature control of localised areas. Heating comes not only from Joule heating but also by being pumped from the reverse face. No moving parts. Small device. Can be used as a cooler in reverse mode.

- disadvantages: Careful mounting required to eliminate large stresses on this relatively fragile device.

C3.3 Assessment of best option

C3.3.1 High heat transfer applications

C3.3.1.1 Indirect heat transfer with precise control

For control, heat pumping capacity, size and ability to cool and heat, Peltier devices are a very attractive option in circumstances where a heat exchanging plate system is chosen. The devices must be cooled on their reverse face for optimum performance and this could be achieved using either a liquid refrigerant circulated through the slip rings or using a cold air stream generated using a vortex tube.

In circumstances where the device is simply being used to trim the plate temperature by a few degrees relative to the refrigerant temperature, the electrical power required is minimal and easily transmitted through slip rings. However, in circumstances where the ability to achieve high temperature differentials is required, a more substantial power supply is required and it is likely that this would have to be mounted on the centrifuge and flown with the package thus incurring an extra overhead.

An alternative system that eliminates the need for Peltier devices is to circulate the refrigerant through a network of channels within a heat exchanging plate and to control the plate temperature by monitoring with thermocouples and adjusting the flow of refrigerant to various parts of the plate using a system of throttling valves under computer control. A system of this nature, however, limits the plate temperature to that of the refrigerant and is thus suitable for medium heat transfer applications

where the cycling of temperatures is not so important (though this of course depends on the temperature at which the refrigerant can be delivered). The valve system may also have to be engineered to cope with very high pressures of refrigerant at the package, if the full head of fluid is allowed to develop along the centrifuge arm.

C3.3.1.2 Direct heat transfer

A vortex tube provides the most straightforward system for providing a direct supply of cold air. Colder temperatures can be achieved using prechilled compressed air such as discussed below in section 3.4. For heating the model, the warm air stream may be used. Precise control of the air stream temperature can be made using an instream heating element with feedback control.

C3.3.2 Low heat transfer applications

For simplicity and convenience, the most attractive option is to circulate refrigerant through a special slip ring set, and cool using a plate system. Alternatively, the need for a heat exchanging plate can be eliminated with the use of a vortex tube which should give a sufficiently large supply of cooling air for low power applications. The air can be simply circulated into the base of the package itself at a constant temperature and vented at the top.

C3.4 Methods of combining cooling systems to achieve lowest possible temperatures.

A liquid refrigerant is clearly capable of absorbing the most heat energy but except for very specialised slip rings it may not be possible to transmit fluid at a temperature below about -40°C. In addition, there will be losses in transmitting the fluid through the piping and the slip ring stack It can be expected that high powers can be achieved at about -35°C at the package. This can be augmented by the use of Peltier devices which could achieve a further cooling of up to about 40°C, depending on the power transfer required.

A vortex tube can give an approximately 50°C temperature drop between the air entering and leaving the device at a pressure ratio of 7:1. Thus pre-cooling the input air will yield a correspondingly colder air output, as will cooling the warm end of the vortex tube (see Otten, 1958). However if the air is prechilled before it passes through the slip rings, it will regain most of its temperature due to conduction from the slip ring stack. One option is to use the liquid refrigerant to prechill the air on the arm, and also to chill the hot end of the vortex tube which should permit very low temperatures to be developed (possibly -90°C) at a relatively high flow rate. On top of this a further drop can be achieved if Peltier devices are used within a cooling plate.

Externally air cooled Peltier devices could also be used on the centrifuge arm to prechill fluids transmitted through the slip rings. Peltier devices may also be stacked to achieve low temperatures. However, since each device pumps not only heat from one face to the other, but also internally generated Joule heat, the stacking must inevitably be of a pyramidal shape. The power requirements and expense then become prohibitive (see Appendix I).

C3.5 Heat exchange within the model

It may be desirable to model such structures as frost heaving pipelines or processes such as shaft freezing within a soil model for which a separate feed of coolant would be required. The connection of an air coolant to the structure is most straightforward mechanically,but consideration needs to be made of the possibly large loss of temperature occurring as the gas flows through the structure. In contrast, a liquid refrigerant will lose much less temperature along a line but is more difficult to connect as it is likely to be under a very high pressure in centrifuge flight. A liquid may also affect instrumentation internal to the structure such as strain gauges.

C4.0 Safety and control

C4.1 Safety

Safety as always is paramount in a centrifuge model test and consideration must be made of the consequences of a failure in control, of an electrical system or of a mechanical component. Several different aspects can be considered as follows.

(i) Failure of temperature sensors/shorting of electrical contacts

This could lead to overchilling or overheating of the package. Overchilling is less likely to be a problem as the minimum temperature achievable within the system should be known. However heat gain could continue to very high temperatures in an insulated package. Overheating could lead to the risk of gross creep deformation of any plastic component such as perspex windows. The melting of insulation and subsequent short circuiting could lead to a fire risk and damage to other wiring in the centrifuge system as a whole and to the slip ring stack. Heating a secondary refrigerant that is contained in a closed circuit could lead to overpressurisation, and over heating a sealed model could lead to generation of pressurised steam.

Most of these effects can be mitigated through protection of electrical circuits with fuses, installation of an independent temperature sensor anywhere where heating is occurring and monitoring of the current load of the package.

(ii) Failure of power supplies

General failure of the power supplies should not in general cause a problem. It is only specific failure of eg. the sensors which may be problematical as discussed above.

(iii) Leakage of refrigerant

A liquid refrigerant will generally be under high pressure during a centrifuge test. Leakage will result in spraying of the fluid over the package or the centrifuge. This may be problematical if the refrigerant chosen is corrosive or toxic. For this reason an inert refrigerant such as silicon oil is recommended. If the refrigerant is being used to cool devices that generate heat then possible overheating as discussed above may occur.

(iv) Failure of slip ring lubrication

If large volumes of compressed air are being supplied to the package through the slip ring stack, then failure of the lubrication system may result in the drying out and subsequent damage to the slip ring seals. The lubrication system therefore needs to be regularly checked.

(v) Temperature effects on mechanical components

Heating will tend to accelerate creep processes especially in plastics, and thermal cycling may result in fatigue effects on highly stressed components, which should be periodically checked.

Chilling will tend to increase the brittleness especially of plastics and again this needs to be considered. Metals such as stainless steel and dural suffer no weakening effects down to very low temperatures.

(vi) Freezing of drains

Freezing of the base drain is only likely to affect the actual model test in progress. However it is important that no leaks occur so that no enclosed volumes of water freeze since due to the 10% expansion of water in its transition to ice, large pressures could be generated sufficient to split perspex fittings.

C4.2 Monitoring and control

The monitoring of the model temperature may be achieved using an array of thermistors/thermocouples logged by a computer running a suitable control program. Where a direct air cooling/heating system is used,it can incorporate a heating element in the air stream under computer control. Alternatively where a heat exchanger plate is used, feedback control is most easily achieved using a cooling fluid to obtain a temperature near to the desired value and then using selectable Peltier devices, heating elements or throttling valves to fine tune the temperatures under computer control. In order to minimise the number of slip ring data channels taken up by this system a multiplexing technique is desirable and could be achieved with 4 datalines :

1. Step
2. Reset
3. Data input from transducer
4. Select Peltier/element voltage or valve flow rate.

Alternatively an on board computer could be used communicating to the control room via a serial data link.

It must be noted that transducers in typical use within a centrifuge model such as pore pressure sensors and strain gauges may be temperature sensitive and thus may require calibration at different temperatures.

An interesting additional application for a Peltier device is as part of a solid state water

valve in the control of a model's drains. Assuming a low flow rate of water within a drain,the flow may be impeded or permitted by freezing or thawing a plug of water using a Peltier device. In order to minimise shear loading on this ice plug, it is necessary that the drain tube not be straight.

C5.0 Implementation of specific systems

In Sections C5 to C7, consideration is given to several possible system implementations, each relating to one of the two major requirements identified in Section C4. These are:

1. An experiment involving a low heat input/output, or simply the maintenance of uniform conditions. This type of experiment will typically be studying the effects of different temperatures on a process or simply eliminating temperature fluctuations in a test.

2. Experiments involving a high heat input/output system where the temperature transients and heat exchange properties are of interest such as in freeze/thaw problems.

In parallel with these requirements, there will be two general approaches to achieving these aims in a model while it is in flight or in preparation:

1. A stand alone package specifically designed for heat transfer experiments with insulated walls and a temperature controlled base and lid, which is used both during model preparation and in an actual test and can be used for both high and low heat transfer studies. Due to its specific design, reconfiguration of existing experimental equipment may be required so that these can fit inside the package, or it may be necessary to consider gaps in the lid through which to pass probes eg., penetrometers.

2. An insulated swinging platform, which will permit the use of existing packages which can be placed within it. This will be difficult to use for high heat transfer modelling but ideal for standard centrifuge studies at specific temperatures. It is desirable to have a swing for sole use on the centrifuge capable of withstanding high accelerations and another lab-floor system with removable wall sand glove boxes for ease of access during model preparation. Within an insulated platform it may still be necessary to insulate the package sides if a thermal gradient is to be modelled.

Section C6 below considers the detailed design of a stand alone centrifuge package configured for high heat transfer tests. This description will be based upon the design and testing of a prototype system in development at Cambridge which will give working experience of several of the cooling options that could be used within a centrifuge package. Section C7 then goes on to consider the design of two insulated platforms, one for use on the lab floor and the other for use on the centrifuge.

C6.0 Stand alone centrifuge package

C6.1 Development of a prototype

A prototype temperature controlled centrifuge package designed to allow testing of several configurations of cooling systems and models has been developed at Cambridge. The package has undergone one centrifuge proof test in order to confirm the functioning of its thermodynamic and electrical systems and to give experience in the use of the equipment. The configuration included a vortex tube, a Peltier cooling array, water cooling and an on board high power supply. Most aspects of the package functioned as expected and the design of the package and its subsequent performance will be discussed in the following sections.

C6.2 Package Design

C6.2.1 Overall design considerations

The package was designed around an existing rectangular dural strongbox with a perspex window designed for use on an Acutronic 661 centrifuge, and of internal dimensions 650 x 390 x 230mm deep. The actual model was to be held within an inner container within this box and separated from the sides by insulation. In order to be able to observe freeze/thaw phenomena occurring in the model in flight and also after a test without removing the model from the box, perspex was chosen for the sides of the inner box and as insulation between the inner box and the perspex window. A small solid state camera was mounted in front of the window.

Cooling was to be achieved within the package using both a vortex tube mounted above the strongbox and a Peltier device array mounted beneath the strongbox lid above the soil surface. The Peltier devices could be gas or liquid cooled and were supplied from a variable power supply under computer control. This mains driven power supply had to be capable of generating high direct currents at relatively low voltages,and so to prevent excessive voltage drop along supply cables or through the slip rings, the power supply was mounted adjacent to the strong box on the centrifuge swing and run in flight.

The air supply for the vortex tube as mentioned in Section C3.1 must be lubricated in order to transmit it safely through the slip rings and so a coalescing air filter was mounted on the side of the package to remove the lubricant before the air passed into the vortex tube. A schematic of the complete package is shown in plan in Fig C.1. Each aspect of the design will now be discussed in detail in the following sections.

C6.2.2 Base plate

The entire system was mounted upon an octagonal 12 mm steel base plate approximately 900mm across, matching the dimensions of the Cambridge beam centrifuge swing.

C6.2.3 Strongbox assembly

C6.2.3.1 Strongbox

As previously mentioned an existing strongbox, designed for use at upto 200 gravities, and of internal dimensions 650 x 390 x 230mm deep and with a perspex window was used. The actual model was to be held within a smaller inner box with perspex sides and isolated from the outer box by insulation. The combined strongbox assembly is depicted in Fig C.2.

C6.2.3.2 Insulation

The insulation chosen below and to the sides of the model was birch plywood which is strong and stiff for its weight, a good insulator and little affected by temperature changes. In order to be able to view the model in flight, a perspex block was placed on one face of the model box between it and the strongbox window instead of the plywood. Above the model where less strength was required, polystyrene foam was used.

C6.2.3.3 Inner box

Sides

The inner box was designed to hold the actual model. In order to model temperature transients well, it was desirable that the box be constructed of an insulating material. It was also desirable that eg. freeze/thaw processes occurring in the model could be seen without removing the model from the box. Perspex was thus chosen for the sides of the box. It is a reasonably good thermal insulator and should cope with the temperature ranges envisaged for the package. The size of perspex box chosen clearly defines the thickness of insulation that can be placed between it and the strong box walls and inevitably involves a compromise between maximum insulation and maximum model size capability. An average thickness of 60mm was chosen. In order that the perspex model box sides were not excessively thick which would be necessary if they had to withstand centrifuge acceleration, it was decided to make them thick enough to cope with model stresses on the lab floor and then to support the sides well with the rigid plywood insulation. This technique was successfully used by Smith, 1992, in the modelling of thaw induced pipeline settlement.

Base

The base has three distinct functions:

- it must act as a constant temperature boundary;

- It must be capable of supplying water to the model box.

- It must be detachable from the box sides so that the entire model, resting upon the base can be removed for sectioning without undue disturbance.

In the current prototype system, only the latter requirement is currently implemented, the other two can be incorporated later as experience with the equipment increases. The base sides are sealed with an o-ring and the base and sides are clamped together using angle section and bolts.

C6.2.4 Air supply and vortex tube

The air supply was drawn from a standard workshop compressor capable of delivering approximately 25 litres/s at 800 kPa. It was passed through a 5 micron coalescing filter, a pressure regulator and a lubricator before being passed through 2 of the centrifuge slip rings in parallel. The lubricant contained in the air delivered to the package was removed by another onboard 5 micron coalescing filter before being delivered to the vortex tube.

The vortex tube was a standard commercially available model supplied by the Vortec Corporation (model 216). It was mounted transversely above the strongbox.

C6.2.5 Heat exchanging plate

As already discussed, the model surface can be cooled directly by a cool air stream or indirectly via a heat exchanging plate. Currently only the indirect cooling system has been developed, and this is discussed in the following section. The subsequent section then discusses the possible implementation of a direct cooling system.

C6.2.5.1 Indirect cooling

Fig C.3 depicts the cooling system currently in use in the Cambridge package. It is based upon Peltier devices cooled by either a cold air stream or a liquid refrigerant. Either cooling system is easily interchanged. The heat exchanging plate is constructed from a 9mm dural sheet, plated black on the side facing the model surface in order to enhance radiative heat transfer, while on the other side, the cold faces of a 5 x 3 array of Peltier devices are attached using thermally conductive paste. An array of this nature gives good coverage of the dural plate and permits a good degree of control over the plates temperature. The hot faces of each row of 5 devices were then put in thermal contact with a dural block through which cooling fluid could be passed. To minimise mechanical loading upon the Peltier devices, the dural block was supported upon steel spacers.

Each row of 3 devices is monitored by a thermocouple and the temperature is computer controlled using feedback signals to a variable power supply. In this way compensation can be made for the warming up of the refrigerant as it flows from one end of the plate to the other or

indeed the maintenance of a small temperature gradient along the plate length is possible if desired. Computer control also enables the smooth cycling of the plate temperature with time, thus permitting simulating of seasonal change.

The Cambridge centrifuge permits dumping of water from the package into the centrifuge pit. Where water is used as a coolant, it may be supplied from the mains at a temperature of approximately 10°C through the slip rings, passed through the cooling blocks and sprayed perpendicularly out of the base of the swing on to the centrifuge pit wall. In a system where water is dumped in this way, cavitation of the fluid tends to occur in the supply lines due to the high pumping action of the centrifuge. In order to reduce this effect, the water was sprayed out through a nozzle to allow some pressure build up at the package. This also had the advantage of ejecting it as a mist so that much of the moisture would be carried away by evaporation into the air circulating through the centrifuge pit.

C6.2.5.2 Direct cooling

Fig C.4 depicts a suggested plate design for direct cooling. The deflection plates hanging from the lid are designed to promote turbulence and so increase heat transfer. This design of lid would be easy to pass instrumentation through, and does not require sophisticated electronic control but may not achieve uniform temperatures across the sample for high heat transfer rates.

C6.2.6 Lid

The lid is an integral part of the strong box and seals the components within. It needs to be stiff enough so that the heat exchanging plate may be suspended from it using lengths of studding, thus permitting vertical displacements of the plate relative to the model surface. It also needs to support junction boxes and vortex tubes. Since the package is sealed in completely, safety of the system is enhanced. The most vulnerable part of the package is the perspex window which must be protected from extremes of temperature which it is however, unlikely to encounter especially when cooled externally in the centrifuge wind.

C6.2.7 Power supply

The ideal power supply unit (PSU) for a the 5 x 3 array of Peltier devices used was one that should be capable of delivering a variable voltage of up to plus/minus 45V @ 6A to 5 independent loads from a AC mains input. Due to space restrictions and components available, a supply capable of producing plus/minus 30V DC @ 25A was constructed. This was then fed through a set of 5 independent power op-amps each under the control of an analogue signal generated by a computer via an D/A converter. It was set up so that applying a negative voltage produced cooling and a positive voltage produced heating.

Due to the high currents being used, it was necessary to mount the PSU adjacent

to the strongbox and fly it during the test. Attempts to supply these currents through the slip rings and accompanying wiring which had resistances of several ohms would produce an excessive voltage loss at the package.

The PSU was therefore designed for centrifuge flight and installed on the swing. Due to the power requirements, the supply was relatively large and weighed 20kg. It was enclosed within a thin steel case for safety and used toroidal transformers to minimise the generation of magnetic fields which can interfere with instrumentation.

In circumstances where the Peltier devices are being used only to trim the temperature by a few degrees, then the necessity for such a large power supply is eliminated and the devices could be controlled directly through the slip rings.

C6.3 Proof test

C6.3.1 Test set up

The proof test was set up primarily to check the performance of the combined thermodynamic, electrical, electronic, mechanical, and control systems under centrifuge accelerations, and to gain experience in the use of the package. A straightforward model of water was setup through which a 6 mm dural tube passed representing a model pipeline. Above the model surface, the water cooled Peltier heat exchanging plate was placed. This had to be positioned 60mm above the water surface to prevent it becoming wetted during swing up and to allow for the curvature of the water surface during flight. In future it may be beneficial to add water to the model in flight. The model pipeline was connected to the vortex tube so that it could be aircooled. As previously stated, it was deemed best to cool actual components of a model under test with air to avoid high pressures or use of a secondary circulating system, while cooling the Peltier devices in the above heat exchanging plate with water. Thermocouples were placed on the strongbox lid, at various positions on the vortex tube, on the air outlet and on the Peltier cooling plate. The test was run over a range of accelerations from 10g to 70g in 10g stages. At each stage the performance of each component was checked for any influence of acceleration, and this is detailed in the following sections.

C6.3.2 Performance of the power supply unit

The main concern of flying a power supply in centrifuge flight is the performance of the large electrolytic smoothing capacitors, which maybe expected to degrade at high accelerations. This degradation was indeed observed with a progressive loss of of the peak voltage produced by the power supply such that it reduced from 30V at 1g to 28V at 70g. The degradation was however partly recoverable as the centrifuge acceleration was reduced. The performance was otherwise excellent and the test helps to confirm that devices such as electrolytic capacitors can be flown successfully.

The power supply itself was designed for general use, however if it were to be dedicated to use with Peltier devices, it is unnecessary to have a power supply

delivering plus/minus 30V. A supply generating between -45V and +10V would suffice unless very high heating rates were required since the heat generating capacity of a Peltier device far exceeds its cooling capacity.

C6.3.3 Performance of the vortex tube

The performance of the Vortex tube did not appear to be affected by the acceleration level. Since the tube was mounted in the open above the strongbox, the thermocouples attached to the tube were affected by the cooling (or warming) effect of the centrifuge wind and could not be used to check changes in the vortex performance. However, the thermocouple monitoring the outlet temperatures of the air after it had been passed through the model pipe was less affected and generally indicated little change at any accelerations. It can therefore be concluded that the vortex tube is little affected by centrifuge acceleration as was expected. The air supply lubrication and filter system worked very well with no problems. It was however observed that the slip rings transmitting these large volumes of air do get quite hot during the test and cooling of these may be desirable for higher flow rates.

C6.3.4 Peltier cooling array performance

The performance of the cooling array did not appear to be affected by the acceleration and a temperature of -25°C was achieved on the plate with the Peltier devices running at about 65% of capacity. The hot faces of the Peltier devices were cooled using a stream of water supplied at about 10°C and flowing at rates between 0.5 litres/sand 2 litres/s. The use of a higher flow rate permitted a lower temperature to be achieved at the plate, in this case giving a 5°C additional drop in temperature over the lower flow rate. At the end of the test no liquid water was seen in the centrifuge pit presumably indicating vaporisation of the water into the air.

C6.3.5 Camera Performance

Due to low light conditions the camera did not perform as well as expected and it was difficult to pick out features from the images. Future tests will include a light source to improve the image quality. Refraction and reflection however, may be a problem.

C6.4 Overall Test Results and Conclusions

Prior to the test, ice cubes were added to the water so that it would start at a temperature near freezing point. However by the time the package had been wired up and placed on the centrifuge swing, the temperatures of the water had increased to 5°C. This meant that during the duration of the relatively short proof test it was only possible to reduce the water temperature by 2 degrees at the base of the model using the two cooling systems. However some ice was observed to form around the inlet end of the model pipe. It is thus necessary to ensure that the model begins the test at a temperature as near to 0°C as possible. It is also preferable to reduce the model surface/heat exchanging plate separation and to further reduce the temperature of the plate in order to speed up cooling rates.

C7.0 Insulated swing package

C7.1 Package concept

This section outlines the design of a rig which would shield a model from pit temperature changes and be capable of maintaining a uniform temperature or small vertical temperature gradient through the model. This can be achieved in an insulated enclosure, modified to suit either application. It will be beneficial to have separate insulated enclosure systems for use both in model preparation on the lab floor and for testing a model in flight. A lab floor system will be considered first and then a corresponding centrifuge enclosure will be discussed.

C7.2 Lab floor system

Model preparation can take place either in hot/cold rooms or in a stand alone enclosure similar to that which would be used on the centrifuge. Each has advantages and disadvantages as follows:

1. Use of hot/cold rooms

   - advantages: Consistent temperature. No fluctuations due to loss of heat/cold when examining kit. Expense.

   - disadvantages: Poor working conditions and need for workers to wear protective clothing. Poor control of thermal gradients. Difficult to saturate models near 0°C. Need to move existing kit preparation equipment into cold/hot room.

2. Use of a stand alone insulated enclosure with glove boxes/ removable sides for easy access.

   - advantages: Can move to existing kit preparation equipment which does not need to cope with extreme temperatures. Good working conditions. Same kit as used on centrifuge so no transfer problems, but easier access. Cheap.

   - disadvantages: Possible excessive temperature transients when preparing models.

If cold rooms are available, these will be useful for certain applications. However, the use of a stand alone insulated enclosure has sufficient benefits to be worth considering. Fig C.5 depicts a possible design for the structure. For long term continuous use on the lab floor it would be best to use an independent chilling unit and circulate a secondary refrigerant to the structure. Each part of the package is discussed as follows:

Base

The base would consist of a metal plate strong enough to take the weight of a typical package, and drilled so that refrigerant could be passed through it. It would then rest upon a thick plywood block for insulation.

Sides and top

These would be constructed of a polyurethane foam sheet sandwiched between mild steel sheets. Two sides and the top would be detachable and be fixed with toggle clips, and sealed with neoprene gaskets. By having detachable sides, easy access is given for construction of the model or for loading the package within. If desired, perspex windows and glove attachments could be placed in the panels.

Heat exchanger plates

Heat exchanger plates can be attached to the two fixed side walls and supplied by an external chiller circulating a secondary refrigerant. For maximum cooling rate, a further loose plate can be placed within beneath the lid and hooked up if necessary.

Fans

For even distribution of air temperatures within the container, electric fans may be placed within to enhance circulation. Additionally if units incorporating heating elements are used then these can be used to heat the enclosure with the chiller unit disconnected.

C7.3 Centrifuge system

The outline design of an insulated centrifuge swing within which existing packages may be placed with little or no modification is discussed below with respect to modelling a uniform temperature or small vertical temperature gradient. The insulated swing will have many of the characteristics of the lab floor system which will not be repeated here.

Fig C.6 indicates the set up for a model maintained at a constant temperature. Air at the correct temperature (from a vortex tube) is blown in to the base of the container and allowed to circulate and vent at the top. As long as even circulation is achieved, the injected air is just that required to overcome external insulation losses and losses in expelled air.

Fig C.7 shows a set up where a small thermal gradient is required from the bottom to the top of the model. The same basic insulation system is used but the package is placed upon a base plate which can be cooled or heated, and surrounded by an insulating jacket to its sides so as to maintain the thermal gradient. Air again is circulated within the top chamber to maintain the temperature. The need to place an insulating jacket around the tub may interfere with other services.

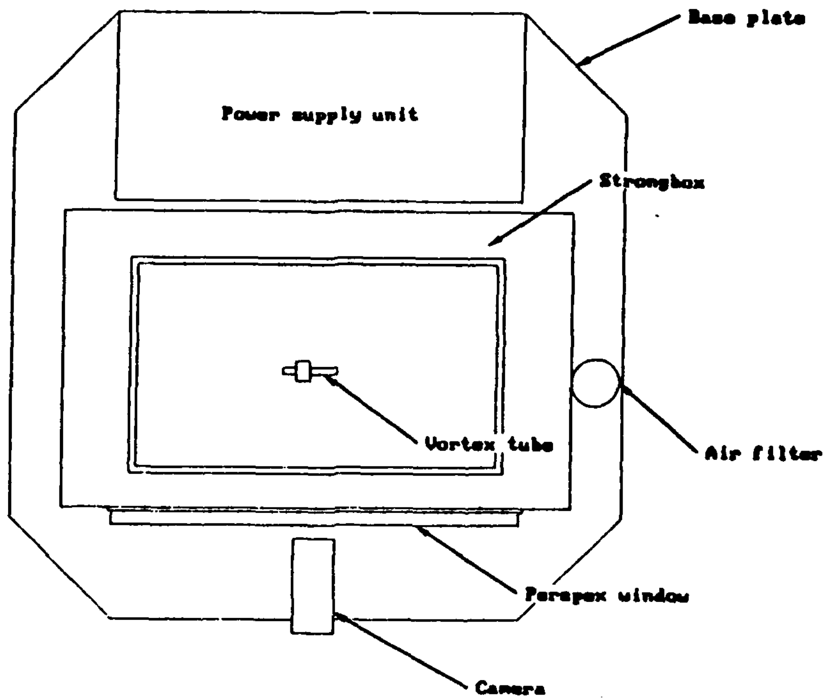


Fig. C1 Schematic of high heat transfer, temperature controlled centrifuge package in plan

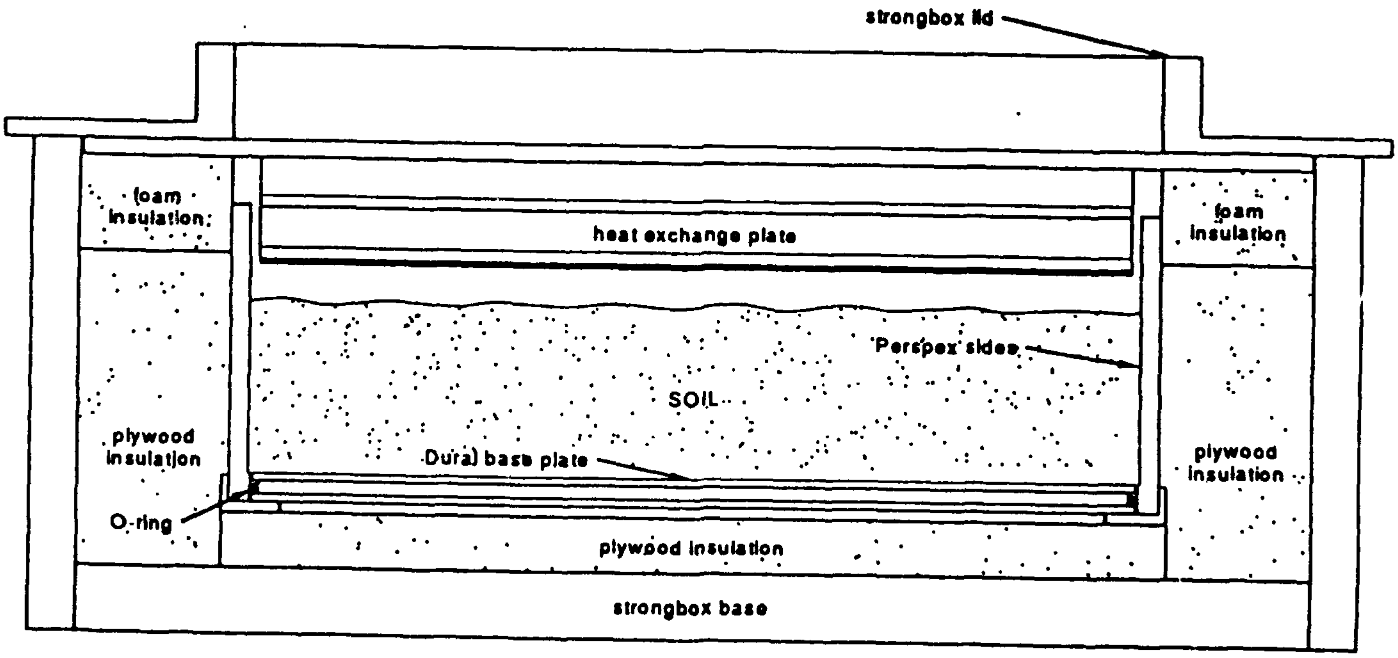


Fig. C2 Schematic elevation of strongbox assembly

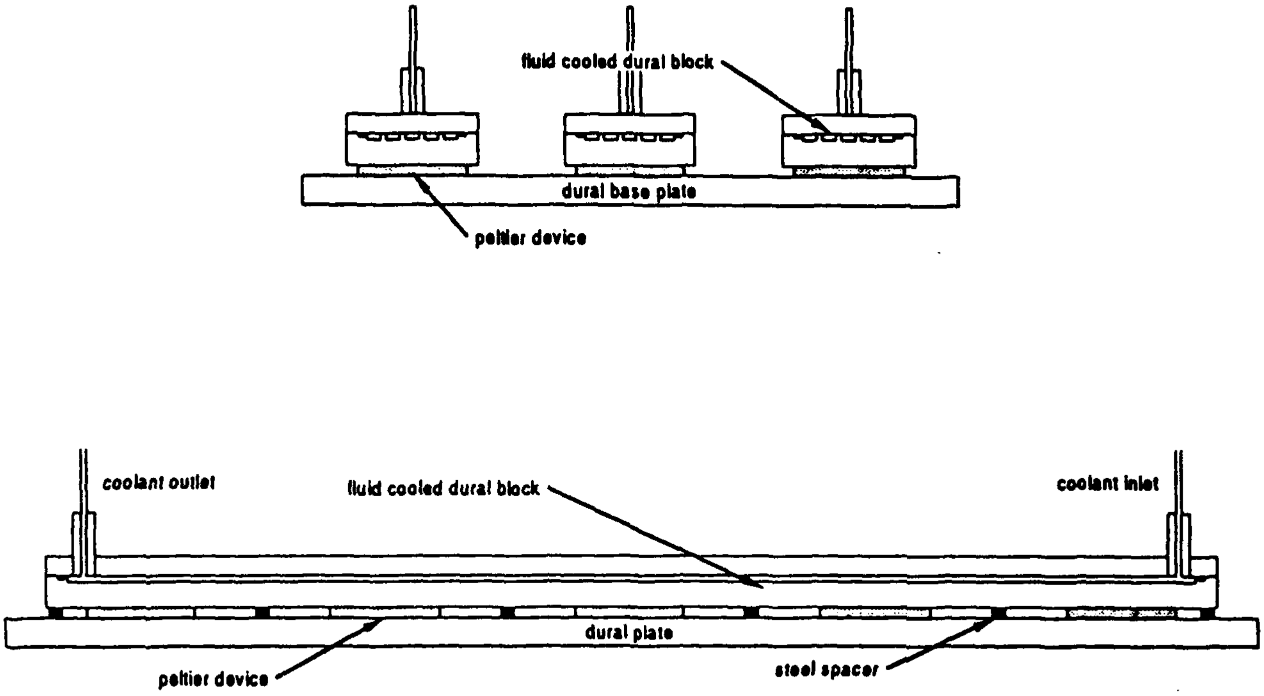


Fig. C3 Schematic of indirect cooling system

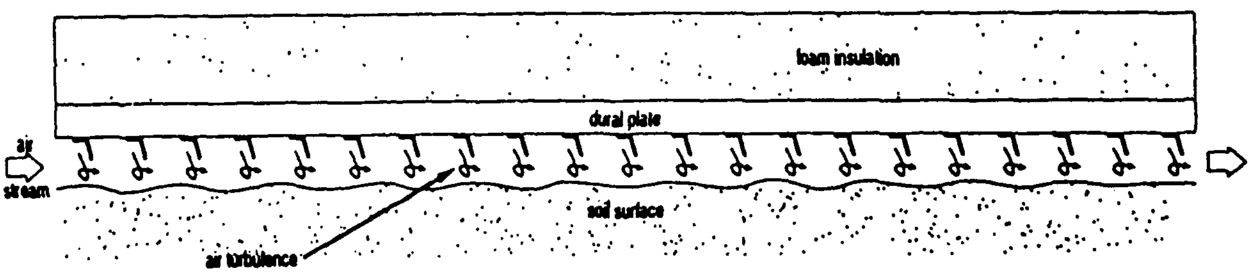


Fig. C4 Schematic of a direct cooling system

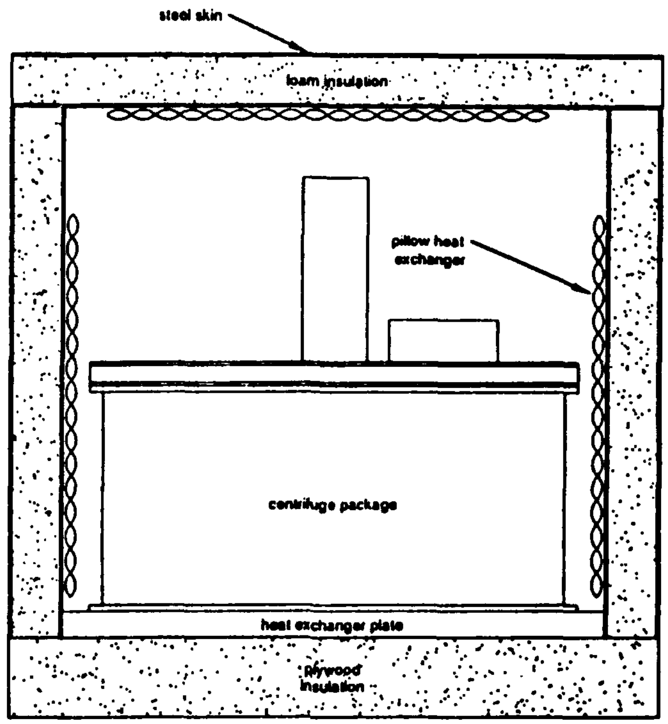


Fig. C5 Lab floor temperature controlled enclosure

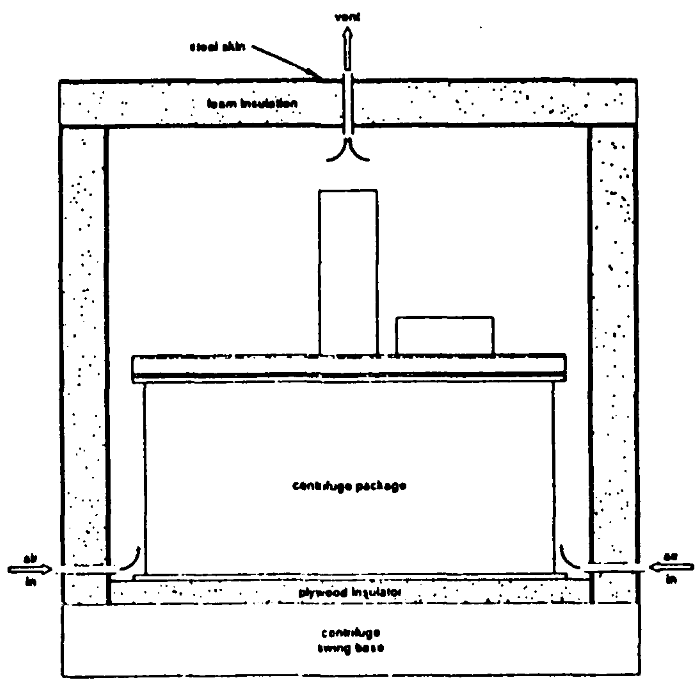


Fig. C6 Insulated centrifuge swing (constant temperature)

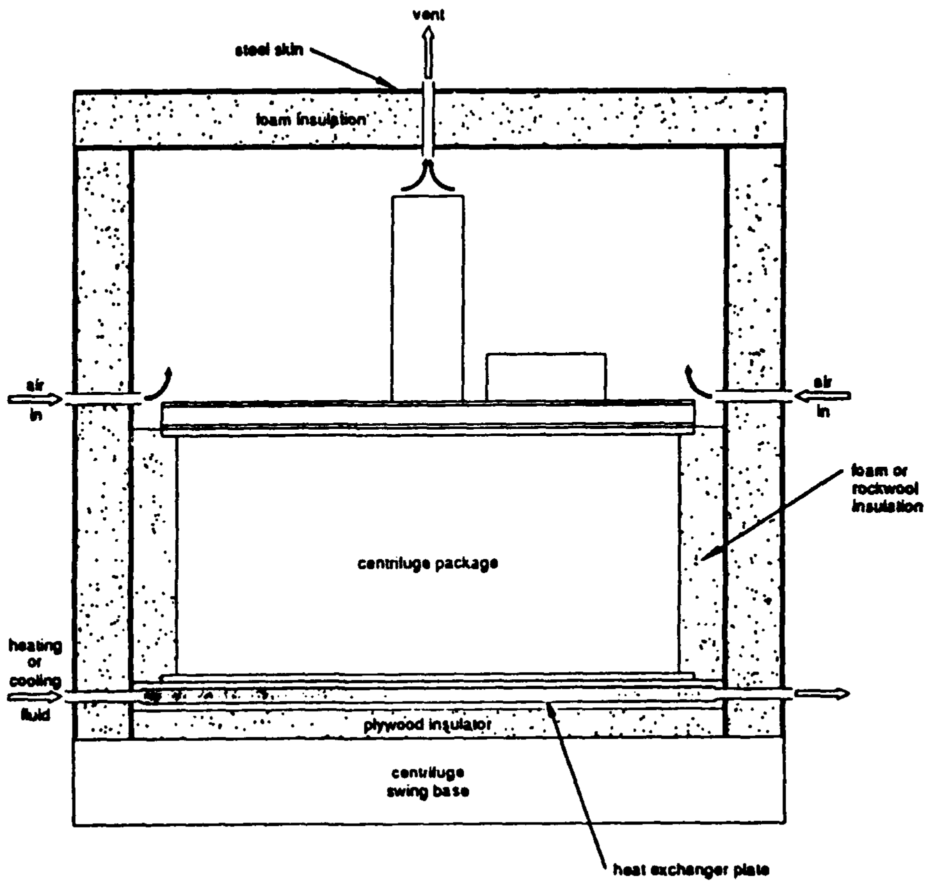


Fig. C7 Insulated centrifuge swing (permitting small thermal gradient)

APPENDIX D

SCALING LAWS FOR TRANSPORT PROCESSES IN SOILS

The following table details centrifuge scaling laws for transport processes in soils. For details of the derivation see for example Smith, 1992.

Physical property	Centrifuge scaling
defined	
macroscopic length	$l_m = l_p/N$
microscopic length	$d_m = d_p$
gravitational acceleration	$g_m = Ng_p$
temperature	$\vartheta_m = \vartheta_p$
derived	
strain	$\varepsilon_m = \varepsilon_p$
pore water pressure	$u_m = u_p$
stress	$\sigma_m = \sigma_p$
time (inertial events)	$t_m = t_p/N$
time (diffusion processes)	$t_m = t_p/N^2$
time (creep processes)	various
total water potential	$P_m = P_p$
interstitial water velocity	$v_m = Nv_p$
moisture flux	$qw_m = Nqw_p$
heat flux	$qh_m = Nqh_p$

APPENDIX E

TYPICAL PROPERTIES OF MATERIALS USED IN CALCULATIONS

Loose quartz sand

Quantity	Symbol	Typical value
void ratio	e	0.9
unfrozen volumetric thermal conductivity	k_u	2.2 W/mK
frozen volumetric thermal conductivity	k_f	4.2 W/mK
dry thermal conductivity	k_d	0.2 W/mK
unfrozen thermal capacity	C_u	3.0 MJ/m^{3}K
frozen thermal capacity	C_f	1.9 MJ/m^{3}K
dry thermal capacity	C_d	1.0 MJ/m^{3}K
volumetric latent heat capacity	L	158 MJ/m^3

Pure water

Quantity	Symbol	Typical value
unfrozen thermal conductivity	k_u	0.56 W/mK
frozen thermal conductivity	k_f	2.2 W/mK
volumetric thermal capacity of water	C_w	4.2 MJ/m^{3}K
volumetric thermal capacity of ice	C_i	1.9 MJ/m^{3}K
volumetric latent heat capacity	L	334 MJ/m^3

Air at 0°C and 1 atmosphere

Quantity	Symbol	Typical value
density	ρ	1.3 kg/m^3
viscosity	υ	1.32 x 10^{-5} m^2/s
thermal conductivity	k	2.4 x 10^{-2} W/mK
thermal diffusivity	α	1.84 x 10^{-5} m^2/s
volumetric thermal capacity	C	1304 J/m^{2}K
thermal capacity at const. pressure	c_p	1.005 x 10^2 J/kgK
Prandtl number	Pr	0.72
gas constant	R	0.287 kJ/kgK

Rock wool or polyurethane foam

Quantity	Symbol	Typical value
density	ρ	approximately 30kg/m^3
thermal conductivity	k	0.04 W/mK
thermal heat capacity	C	0.04 MJ/m^{3}K

APPENDIX F

HEAT INPUT/OUTPUT TO SOIL/ICE

F1.0 Cold regions: cyclic surface temperatures - annual freeze thaw

In this section, an estimate is made for the heat fluxes required in the modelling of an annual freeze thaw cycle. The approximate solution method used, follows after Harlan and Nixon, 1978, and uses the concept of a thaw index Ith.

Let the equation describing the annual variation of ground surface temperature with time be as follows:

$$T_s = T_g + a_0 \sin\left(\frac{2\pi t}{Y}\right)$$

where Y = 365 days is the period of the freeze/thaw cycle and t_0 is the time at which the surface is above freezing

$$t_0 = \frac{Y}{2\pi} \sin^{-1}\left(\frac{T_f - T_g}{a_0}\right)$$

The thaw index is given by:

$$I_{th} = \int_{t_0}^{t} (T_s - T_f)\, dt$$

and the thawing/freezing depth X is given by:

$$X = \left(\frac{2k_u T_{th}}{L}\right)^{0.5}$$

The Stefan number is:

$St = C_u T_s / L.$

Let $T_g = 0°C$,

$$T_s = a_0 \sin \frac{2\pi t}{Y}$$

$$I_{th} = \int_0^t a_0 \sin \frac{2\pi t}{Y} dt$$

$$= -\frac{a_0 Y}{2\pi}\left\{\cos \frac{2\pi t}{Y} - 1\right\}$$

$$X = \left(\frac{2k_u I_{th}}{L}\right)^{0.5}$$

$$= \left(\frac{a_0 Y k_u}{\pi L}\left(1 - \cos \frac{2\pi t}{Y}\right)\right)^{0.5}$$

The heat flux rate is given by $L\, dX/dt$

$$= \left(\frac{L a_0 k_u \pi}{Y}\right)^{0.5} \sin \frac{2\pi t}{Y} \left(1 - \cos \frac{2\pi t}{Y}\right)^{-0.5}$$

let $M = \left(\frac{L a_0 k \pi}{Y}\right)^{0.5}$ and $N = \left(\frac{a_0 Y k}{\pi L}\right)^{0.5}$

Hence the variation of the heat flux rate with time is as follows:

$\frac{2\pi t}{Y}$	flux/M
0°	1.41
30°	1.37
60°	1.22
90°	1
180°	0

Therefore $(q_{prot})_{max} = 1.41M$ and $(q_{model})_{max} = 1.41nM$ where n is the model scale factor.

For values of $a_0 = 10°C$ and $Y = 31.6 \times 10^6$ s (1 year), the following values of M and N can be calculated:

material	freeze/thaw	M (W/m^2)	N(m)
quartz soil	thawing	18.73	1.17
quartz soil	freezing	25.94	1.62
sea ice	thawing	13.66	0.41
sea ice	freezing	27.05	0.81

F2.0 Geothermal soil flux

A typical thermal gradient for the earth is 1°C/50m which at a scale of 100g is 1°C/500mm.

In frozen loose quartz soil, this gives a flux of:

$$\frac{k\Delta t}{l} = 8.4\ W/m^2$$

APPENDIX G

HEAT TRANSFER TO MODEL SURFACE

This appendix concerns the indirect heat transfer of energy from a heat exchanging plate to a model surface through a small air gap. It considers conduction, convection, and radiation.

G1.0 Pure conduction between model surface and heat exchanging plate

Let temperature of the top plate be T_p, temperature of soil surface be T_s, and the gap between the two be H, then the heat transfer due to pure conduction is given by

$$q_{cond} = \frac{k\Delta T}{H}$$

where $\Delta T = T_s - T_p$.

For example if $T_p = -50°C$, $T_s = 0°C$ and $H = 0.02m$, then for $k = 0.022$ W/mK, $q_{cond} = 55$ W/m^2.

G2.0 Natural convection between soil surface and cold plate

If $T_s > T_p$ then natural convection will take place. The process is governed by the Rayleigh number Holman, (1981), p 291.

$$Ra_H = \frac{ng\beta H^3 \Delta T}{\alpha \upsilon}$$

For an ideal gas, $\beta = 1/T$ where T is in Kelvin. Hence

$$Ra_H \approx \frac{ngH^3 \Delta T}{\alpha \upsilon \overline{T}}$$

where $\overline{T} = (T_s - T_p)/2$, ng is the centrifuge acceleration. An empirical correlation can be

given relating the Nusselt number, the ratio of convective heat transfer to conductive heat transfer, to the Rayleigh number as follows:

$$Nu = \frac{k_e}{k} = CRa_H^m$$

where for parallel horizontal plates, empirical correlations are as follows:

Ra_H	C	m
<1700	1	0
1700 to 7000	0.059	0.4
7000 to 3.2×10^5	0.212	0.25
$> 3.2 \times 10^5$	0.061	0.33

where $0.5 < Pr < 2$, $(Pr = \upsilon/\alpha)$. And for the case of $T_p > T_s$, C = 1, m = 0. Hence

$q_{conv} = Nu\ q_{cond}$.

For example if $T_p = -50°C$, $T_s = 0°C$, $H = 0.02$ m, and n = 50 then $q_{conv} \approx 600\ W/m^2$.

It is seen that for Rayleigh numbers greater than 3.2×10^5 then the heat transfer by convection is independent of the height H, permitting a large air gap to be maintained between soil surface and top plate in these circumstances. It must be noted that in a centrifuge test involving a free water surface, this surface will be curved, and this may need to be accounted for in the shape of the top plate. In addition the results will be modified somewhat by the presence of Coriolis effects.

In order to improve the heat transfer at lower Rayleigh numbers a different gas with greater thermal conductivity could be used in the air gap between model and top plate as long as a good seal was maintained. Of those available only Helium would be useful and safe. The relevant properties of air and helium at about 250K are listed in the below table.

gas	temperature K	ρ kg/m^3	υ m^2/s	k W/mK	α m^2/s
air	250	1.41	9.49×10^{-6}	0.022	0.132×10^{-4}
helium	255	0.19	95.5×10^{-6}	0.136	1.36×10^{-4}

It can be seen that the thermal conductivity of helium is roughly 6 times larger than that of air, however, due to the increased viscosity and thermal diffusivity there is a large reduction in its convective heat transfer potential. However in all cases the use of

helium will improve the the heat transfer.

G3.0 Radiative heat transfer

The calculation of the magnitude of heat transfer occurring if both surfaces can be considered as black bodies (this is a fairly close approximation), is given by:

$$q_{rad} = \sigma\left(T_2^4 - T_1^4\right) AF$$

where $\sigma = 56.7 \times 10^{-9}$ W/m^{2}K^4. For radiative heat transfer between a matt black plate and a dark model surface, the transmittance coefficient F will be about 0.95. For example taking $T_1 = -50°C = 223$ K, $T_2 = 0°C = 273$ K, $F \approx 0.95$, and assuming a plate separation small relative to the plate area then

$$q = 174.7 \text{ W/m}^2$$

G4.0 Combined convective, conductive and radiative heat transfer

Where the model surface is warmer than the heat exchanging plate, then the maximum heat transfer that can be obtained is given by $q_{conv}+q_{rad}$. However in circumstances where the plate is warmer than the model then convection cannot take place and transfer is by conduction and radiation only: $q_{cond} + q_{rad}$.

In centrifuge models, the intent is typically to simulate a prototype system. If the prototype heat flux is known, qprot, then the required model heat flux rate is $n(q_{prot})$ (see Section 7). Hence it is of value to replot the relationship between ΔT and the acceleration for various values of q_{prot} so that for a given q_{prot} and test acceleration, the temperature gradient ΔT can be determined. A plot is given in G.1 for a plate separation of 0.05 m where the soil temperature is taken as 0°C. It can be seen that smaller temperature differences are needed for cooling as compared to heating eg. for a required prototype heat flux of 15 W/m^2, at a model acceleration of 50g requires a ΔT of -50°C for cooling and 95°C for heating is required.

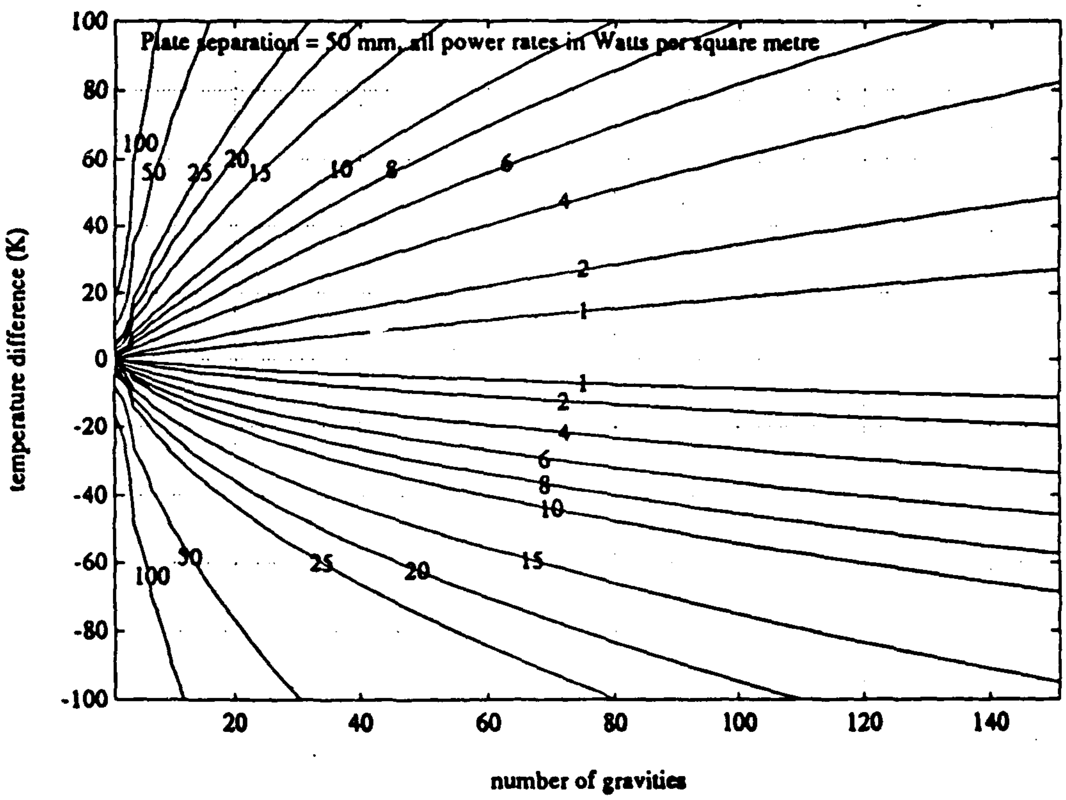


Fig. G1 Plot of prototype heat transfer rates achievable as a function of temperature difference and centrifuge acceleration

APPENDIX H

COOLING WITH A GAS FLOW

H1.0 Cooling with a vortex tube

A vortex tube (as depicted in Fig H.1) converts compressed air into two airstreams, one hot and one cold. It has no moving parts and is therefore well suited to use on a centrifuge. The volume and temperature of the cold air produced by a vortex tube are controlled by the inlet/outlet pressure ratio and by a valve in the hot air exhaust. A low cold air flow produces the lowest temperatures, while higher flows produce correspondingly higher temperatures. While not as efficient at producing cold air as a turbine, it can still generate up to a 75°C temperature drop for a pressure ratio of 10:1.

Commercially available vortex tubes can work with total flow rates (cold and warm air streams) from 1 to 50 standard litres per second.

H2.0 Direct heat transfer using a cold/hot 'wind'

The direct cooling of a model surface can be achieved by blowing a cold/hot air stream through a relatively narrow gap between the model surface and an insulated plate. The height of the gap, velocity of the air stream, and the presence of any turbulence promoting devices will determine the actual heat transfer rate. An empirical relation for the heat transferred from a fluid flowing between two parallel plates (see for example Holman, 1981) can be used to give an estimate of the heat transfer rates. An example calculation for this heat transfer rate due to an air stream at T_b = -40°C, supplied at Q = 10 litres/s, passing through a gap between a model surface of temperature T_s = 0°C and an insulated plate of width w = 200 mm, and length l = 500 mm is given below, where the gap between the plates is g = 20 mm.

Entry properties of the air:

$\rho = 1.6$ kg/m^3,
Pr = 0.73,
$\mu = 1.4 \times 10^{-5}$ kg/m.s ,
k = 0.02 W/mK ,
c_p = 1006 J/kg.K .

The equivalent hydraulic diameter D_H is given by

$$D_H = 4A/P = 0.023 \text{ m} ,$$

where A is the gap area, and P is the gap perimeter. The flow velocity v is given by

$$v = Q/A = 4.2 \text{ m/s}$$

giving a Reynolds number of Re = 10800.

The flow is therefore turbulent, and the following equation can be used to calculate the heat-transfer coefficient:

$$Nu_d = \frac{hd}{k} = 0.023\, Re_d^{0.8}\, Pr^{0.4} = 34.2$$

$$h = \frac{k}{d} Nu_d = 30.2 \text{ W/m}^2\text{K}$$

Hence the heat flow per unit length is given by

$$q/L = hw(T_s - T_b) = 300 \text{ W/m},$$

which is equivalent to a heat transfer rate of 1.5 kW/m^2. The increase in bulk temperature of the air is given by

$$\Delta T_b = \frac{1}{\rho Q C_p} \frac{q}{L} = 10°\text{C} .$$

This will have some effect on the uniform cooling of the model surface. There may also be difficulty in producing a uniform wind across a wide area.

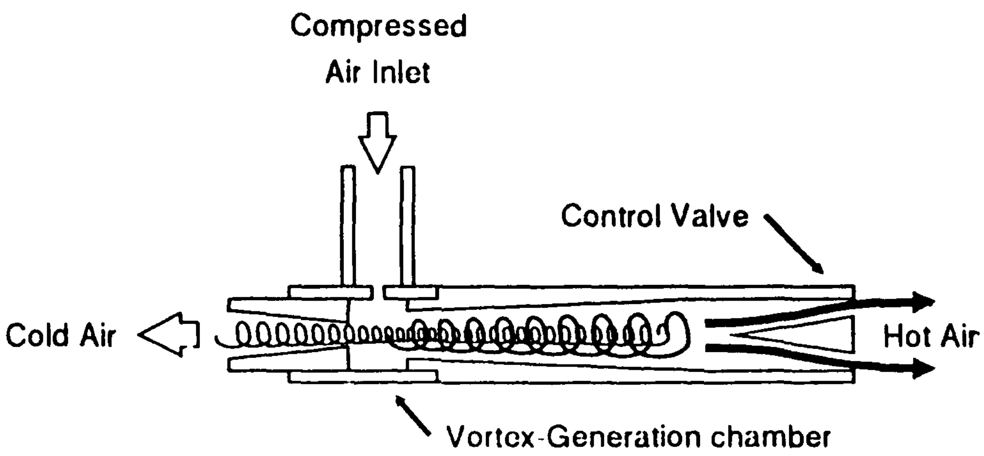


Fig. H1 The principle of the vortex tube

APPENDIX I

COOLING WITH PELTIER DEVICES

I1.0 Peltier devices

A Peltier heat pump is a solid state thermoelectric element capable of pumping heat from one face to the other with the expenditure of electrical work. This is typically achieved using a low voltage and a large current supply and the device is typically a flat plate a few millimetres in thickness. It works essentially like a thermocouple in reverse. Such a device can typically pump up to 38 kW/m^2 or maintain up to a 70°C temperature difference across its faces. However there is a trade off in achieving both these goals: the consumption of electrical power for the maximum performance is of the order of 40 kW/m^2.

The heat rejected by a Peltier device onto one of its faces must be removed in order to prevent excessive temperature build up. Cooling may be achieved using air or liquid cooling streams as detailed in the following subsections. In general the heat will be exchanged from the fluid to an intermediate plate which is in thermal contact with the hot faces of the Peltier devices.

I2.0 Air cooling of Peltier devices

An empirical equation for the heat transfer in flow between two parallel plates will be used to compute a typical heat extraction rate possible with air. This calculation follows very similarly to that given in Appendix H. An example is given below for the cooling of a plate of width w = 48mm, length l = 500mm, which is in thermal contact with several Peltier devices, which are pumping heat into the plate at a rate of 200 W/m. An air stream of Q = 4 litres/s, T_b = -40°C is blown between this plate and an insulated parallel plate through a gap of height h = 3 mm. Entry properties of the air:

$\rho = 1.6\ kg/m^3$,
$Pr = 0.73$,
$\mu = 1.4 \times 10^{-5}\ kg/m.s$,
$k = 0.02\ W/mK$,
$c_p = 1006\ J/kg.K$.

The equivalent hydraulic diameter D_H is given by

$D_H = 4A/P = 0.0056$ m ,

the flow velocity v is given by

$v = Q/A = 27.8$ m/s,

giving a Reynolds number of

$Re = 18000$.

The flow is therefore turbulent, the following equation can be used to calculate the heat-transfer coefficient:

$$Nu_d = \frac{hd}{k} = 0.023\, Re_d^{0.8}\, Pr^{0.4} = 51.4$$

$$h = \frac{k}{d} Nu_d = 182 \text{ W/m}^2\text{K}$$

Hence the required temperature difference between air stream and plate to give a heat transfer rate of 200 W/m is given by

$$(T_s - T_b) = \frac{q}{hw} = 23^\circ\text{C} .$$

The increase in bulk temperature of the air is given by

$$\Delta T_b = \frac{l}{\rho Q c_p} \frac{q}{L} = 16^\circ\text{C} .$$

This will have some effect on the uniform cooling of the plate surface. A more sophisticated calculation could be performed. This calculation is merely intended as a guide to the cooling rates possible.

13.0 Cooling of Peltier devices with liquid

A similar calculation to that for the air cooling of a Peltier device can be performed in the case of liquid cooling. Take for example the case of a plate cooled by water supplied to it at a temperature $T_b = 5^\circ$C and at a rate of 0.01 litres/s. The water will be passed through a channel within the plate of width w = 45 mm, height g = 2 mm and length l = 500 mm. It is required to extract heat from the plate at a rate of 500 W/m. This heat flux figure exceeds that for the air due to the larger heat capacity of a liquid but also due to the higher liquid temperature considered, thus requiring a bigger temperature difference to be maintained by the Peltier device and therefore a correspondingly higher electrical workload. Entry properties of the water:

$\rho = 999.8 \text{ kg/m}^3$,
$Pr = 11.35$,
$\mu = 1.55 \times 10^{-3}$ kg/m.s ,
$k = 0.58$ W/mK ,
$c_p = 4200$ J/kg.K .

The equivalent hydraulic diameter D_H is given by

$D_H = 4A/P = 0.0038$ m,

the flow velocity v is given by

$v = Q/A = 0.11$ m/s,

giving a Reynolds number of

$Re = 270.$

The flow is therefore laminar, the following equation can be used to calculate the heat-transfer coefficient:

$$Nu_d = \frac{hd}{k} = 1.86\,(Re_d Pr)^{0.33} \left(\frac{D_H}{L}\right)^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14} = 5.3 \ ,$$

$$h = \frac{k}{d} Nu_d = 810 \text{ W/m}^2\text{K}$$

Hence the required temperature difference between air stream and plate to give a heat transfer rate of 500 W/m is given by

$$(T_s - T_b) = \frac{q}{hw} = 13^\circ\text{C} \ ,$$

The increase in bulk temperature of the air is given by

$$\Delta T_b = \frac{1}{\rho Q c_p} \frac{q}{L} = 6^\circ\text{C} \ .$$

Improvement of these figures can be made through optimising the water flow pattern within the plate.

APPENDIX J

HEAT LOSS THROUGH INSULATION

The approximate heat loss from a package of average internal temperature T_i, insulated by t m of material of conductivity k to the centrifuge pit temperature of T_e can be given by

$$q = \frac{k(T_i - T_e)}{t} \text{ per unit area}$$

Thus where a package with an average model temperature of -30°C is insulated by 100 mm of polyurethane foam insulation (k = 0.04 W/mK) and is tested in a centrifuge pit of temperature of 50°C, the heat flux entering the package will be approximately 32 W/m^2.